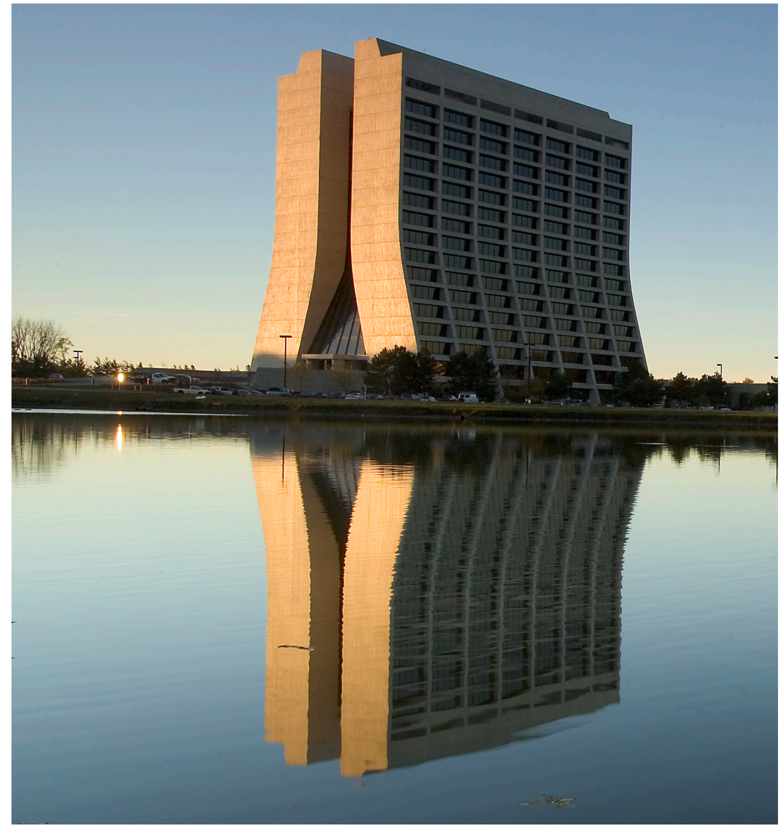
100 TeV
PDFs for ~~the LHC~~

Joey Huston
Michigan State University



References:

- J. Rojo: kickoff meeting for FCC at CERN, Feb. 2014
- Snowmass QCD writeup: arXiv:1310.5189
- Les Houches session 1 writeup: arxiv:1405.1067

Some history: PDF4LHC

- In 2010, we carried out an exercise to which all PDF groups were invited to participate
- A comparison of NLO predictions for benchmark cross sections at the LHC (7 TeV) using MCFM with prescribed input files
- Benchmarks included
  - W/Z production/rapidity distributions
  - ttbar production
  - Higgs production through gg fusion
    - masses of 120, 180 and 240 GeV
- PDFs used include CTEQ6.6, MSTW08, NNPDF2.0, HERAPDF1.0 ABKM09, GJR08
- Results in Higgs YR1 and YR2

The PDF4LHC Working Group Interim Report

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arXiv:1101.0536v1 [hep-ph] 3 Jan 2011

All of the benchmark processes were to be calculated with the following settings:

1. at NLO in the $\overline{MS}$ scheme
2. all calculation done in a the 5-flavor quark ZM-VFNS scheme, though each group uses a different treatment of heavy quarks
3. at a center-of-mass energy of 7 TeV
4. for the central value predictions, and for $\pm 68\%$ and $\pm 90\%$ c.l. PDF uncertainties
5. with and without the α_s uncertainties, with the prescription for combining the PDF and α_s errors to be specified
6. repeating the calculation with a central value of $\alpha_s(m_Z)$ of 0.119.

Recommendations:arxiv:1101.0538

So the prescription for NLO is as follows:

- For the calculation of uncertainties at the LHC, use the envelope provided by the central values and PDF+α_s errors from the MSTW08, CTEQ6.6 and NNPDF2.0 PDFs, using each group's prescriptions for combining the two types of errors. We propose this definition of an envelope because the deviations between the predictions are as large as their uncertainties. As a central value, use the midpoint of this envelope. We recommend that a 68%c.l. uncertainty envelope be calculated and the α_s variation suggested is consistent with this. Note that the CTEQ6.6 set has uncertainties and α_s variations provided only at 90%c.l. and thus their uncertainties should be reduced by a factor of 1.645 for 68%c.l.. Within the quadratic approximation, this procedure is completely correct.

Note each PDF uses native value of $\alpha_s(m_Z)$ and PDF+α_s errors around that central choice.

So the prescription at NNLO is:

- As a central value, use the MSTW08 prediction. As an uncertainty, take the same percentage uncertainty on this NNLO prediction as found using the NLO uncertainty prescription given above.

Followup in 2013

- Study of NNLO PDFs from 5 PDF groups (no new updates for JR)
  - drawing from what Graeme Watt had done at NNLO, but now including CT10 NNLO, and NNPDF2.3 NNLO
    - HERAPDF has upgraded to HERAPDF1.5; ABM09->ABM11
  - using a common values of α_s (0.118) as a baseline; varying in range from 0.117 to 0.119)
  - including a detailed comparisons to LHC data which have provided detailed correlated systematic error information, keeping track of required systematic error shifts, normalizations, etc
    - ATLAS 2010 W/Z rapidity distributions
    - ATLAS 2010 inclusive jet cross section data
    - CMS 2011 W lepton asymmetry
    - LHCb 2010 W lepton rapidity distributions in forward region
- The effort was led by Juan Rojo and Pavel Nadolsky and has resulted in an independent publication
- The results from this paper will be utilized in a subsequent PDF4LHC document(s)
- …and are now in YR3

Benchmark paper

- Not officially a PDF4LHC document but used as input for current PDF4LHC recommendation
- Comparisons only at NNLO, but NLO comparisons available at http://nnpdf.hepforge.org/html/pdfbench/catalog

CERN-PH-TH/2012-263
Edinburgh 2012/21
SMU-HEP-12-16
LCTS/2012-26
IFUM-1003-FT

Parton distribution benchmarking with LHC data

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Abstract:

We present a detailed comparison of the most recent sets of NNLO PDFs from the ABM, CT, HERAPDF, MSTW and NNPDF collaborations. We compare parton distributions at low and high scales and parton luminosities relevant for LHC phenomenology. We study the PDF dependence of LHC benchmark inclusive cross sections and differential distributions for electroweak boson and jet production in the cases in which the experimental covariance matrix is available. We quantify the agreement between data and theory by computing the χ^2 for each data set with all the various PDFs. PDF com-

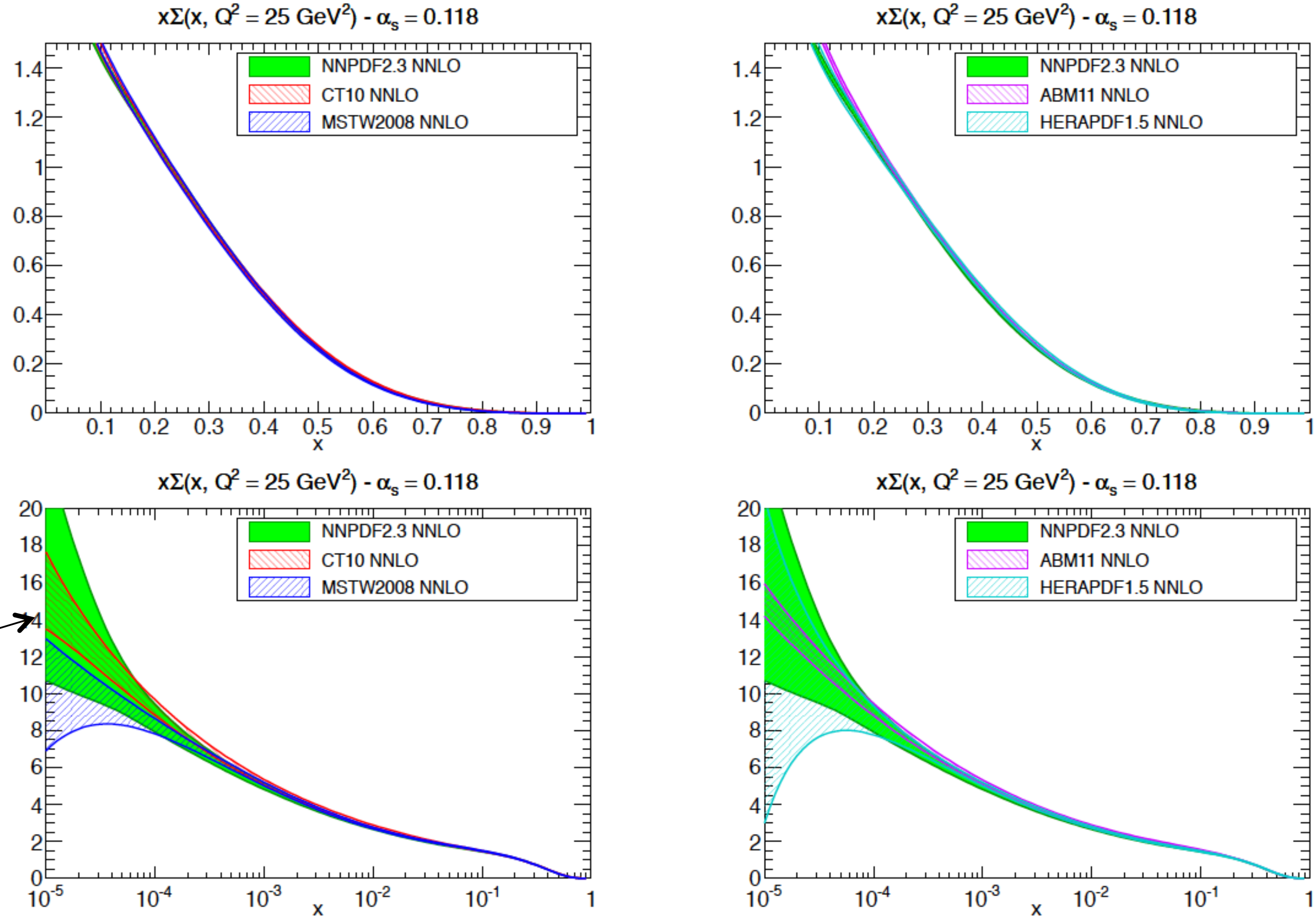
PDF comparisons

quark singlet PDFs

...results for other values of α_s and at NLO available on the HEPFORGE website

good agreement for all sets for quark singlet distribution

note the blowup of uncertainties for low x



Comparison of PDFs

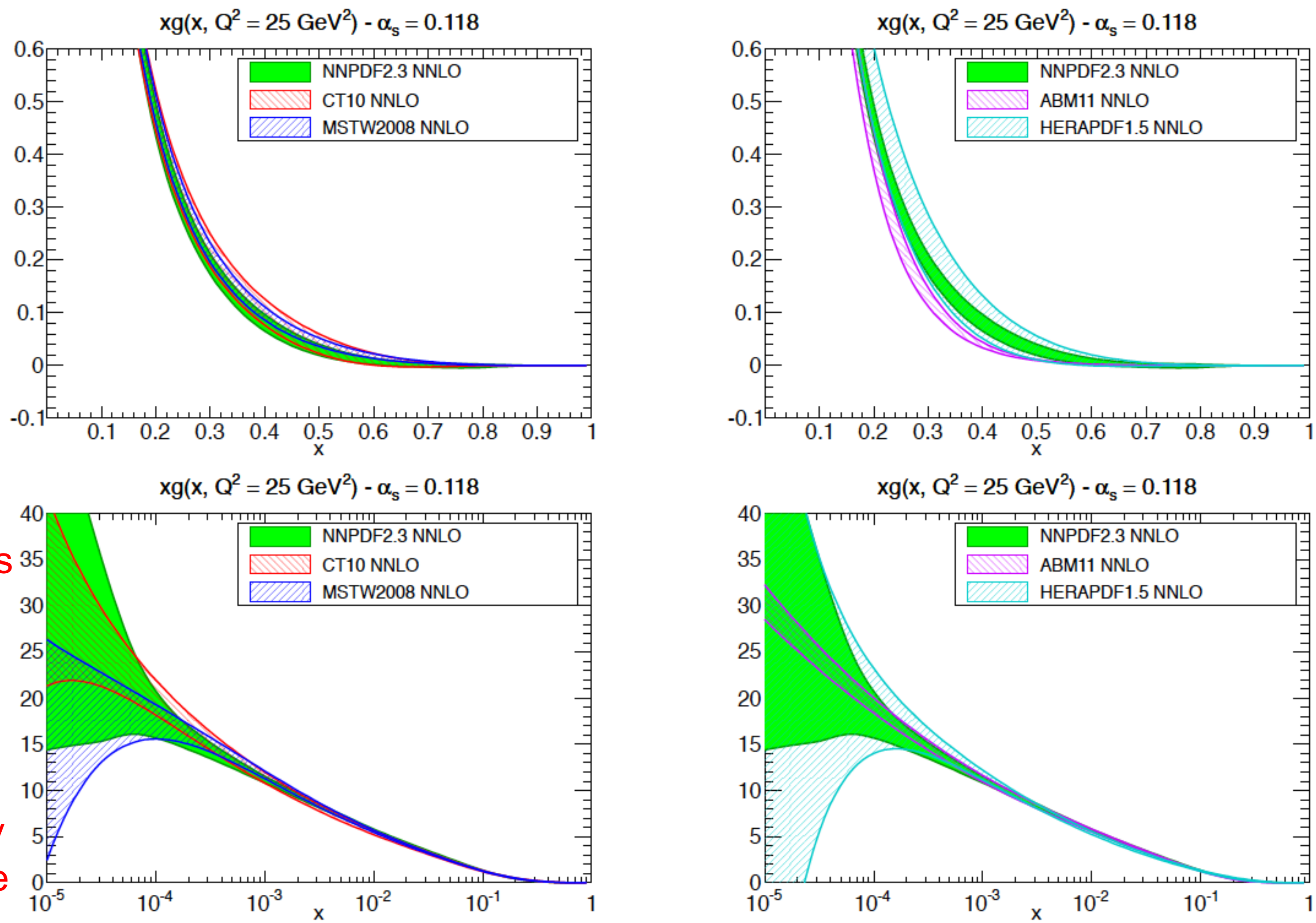
CT10, MSTW08 and NNPDF2.3 gluon distributions all in reasonable, but not perfect, agreement

The 1-sigma uncertainty bands overlap for all values of x

again, uncertainties blow up for small x

HERAPDF uncertainties somewhat larger at low x; noticeably larger at high x due to lack of collider jet data

gluon PDF



PDF luminosities

gluon-gluon and gluon-quark luminosities in reasonable, but again not perfect, agreement for CT10, MSTW08 and NNPDF2.3 for full range of invariant masses

HERAPDF1.5 uncertainties larger in general

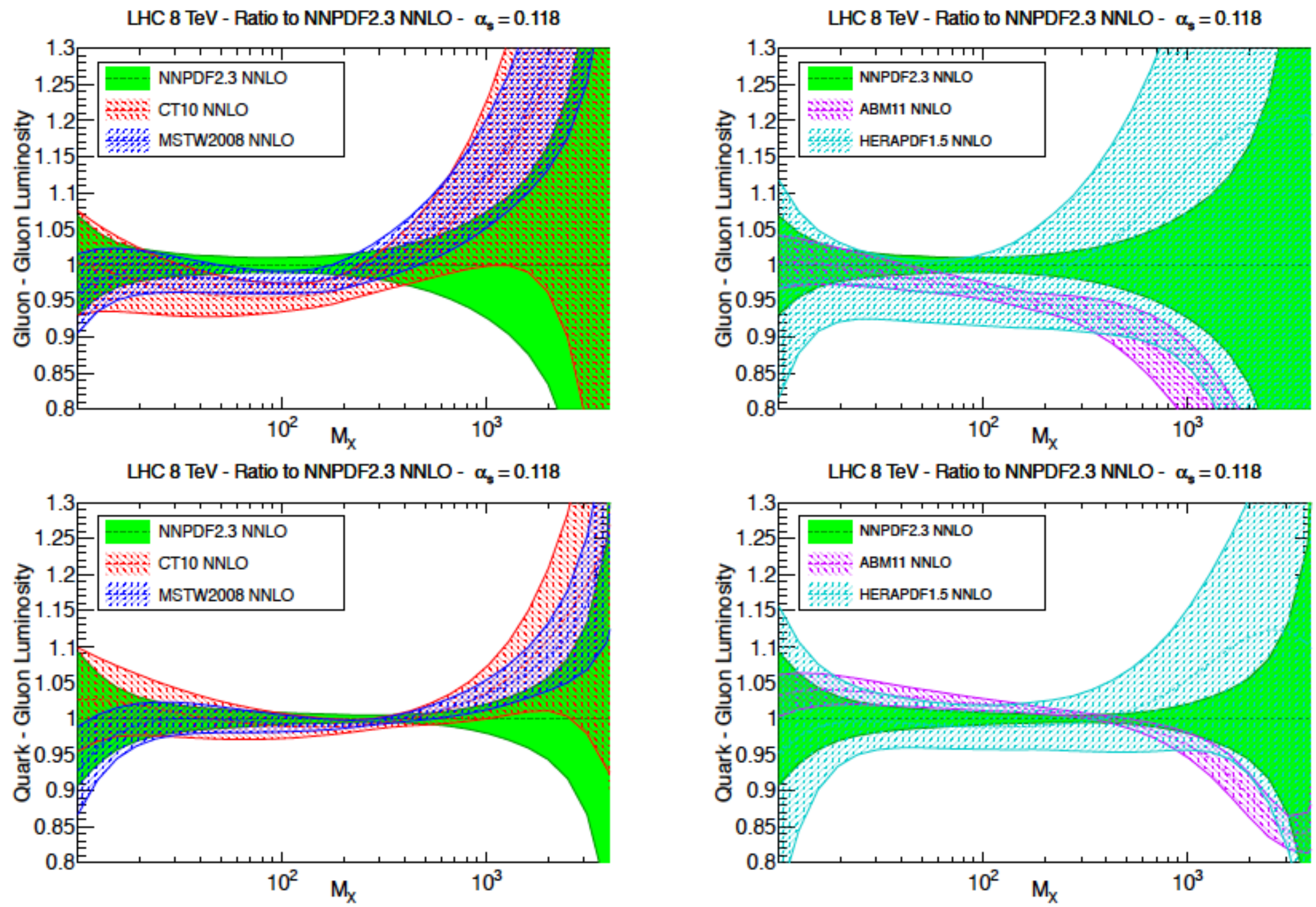
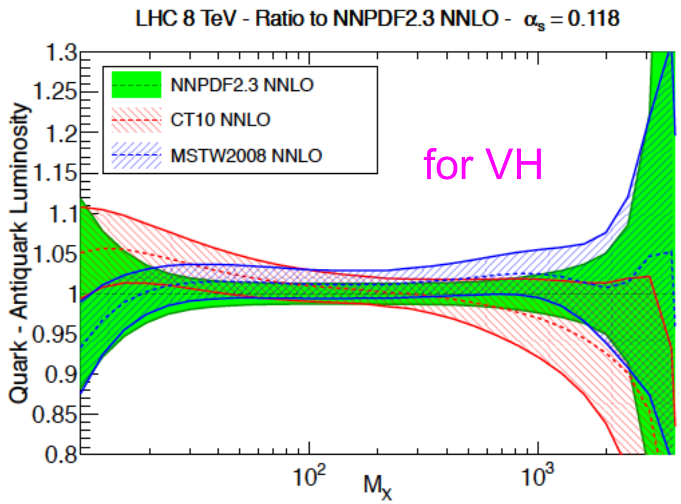


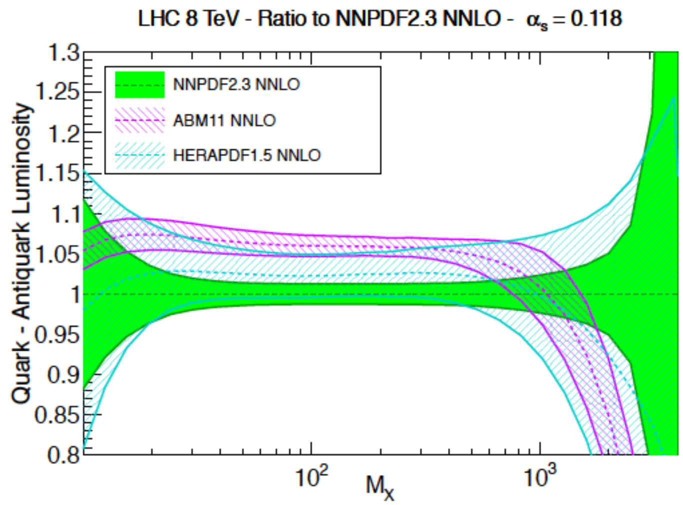
Figure 6: The gluon-gluon (upper plots) and quark-gluon (lower plots) luminosities, Eq. (2), for the production of a final state of invariant mass M_X (in GeV) at LHC 8 TeV. The left plots show the comparison between NNPDF2.3, CT10 and MSTW08, while in the right plots we compare NNPDF2.3, HERAPDF1.5 and MSTW08. All luminosities are computed at a common value of $\alpha_s = 0.118$.

PDF luminosities

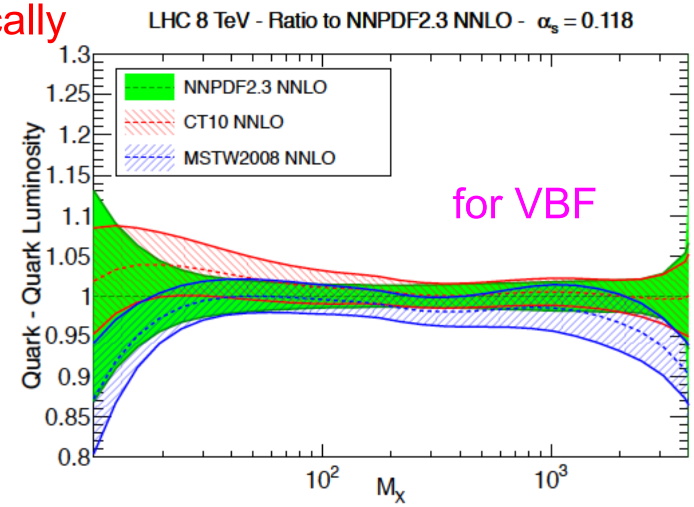
quark-quark and quark-antiquark

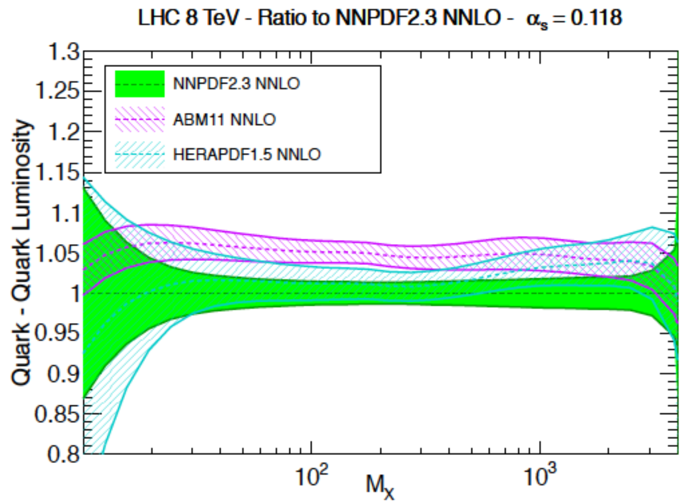
quark-antiquark luminosities for CT10, MSTW08 and NNPDF2.3 overlap almost 100% in W/Z range





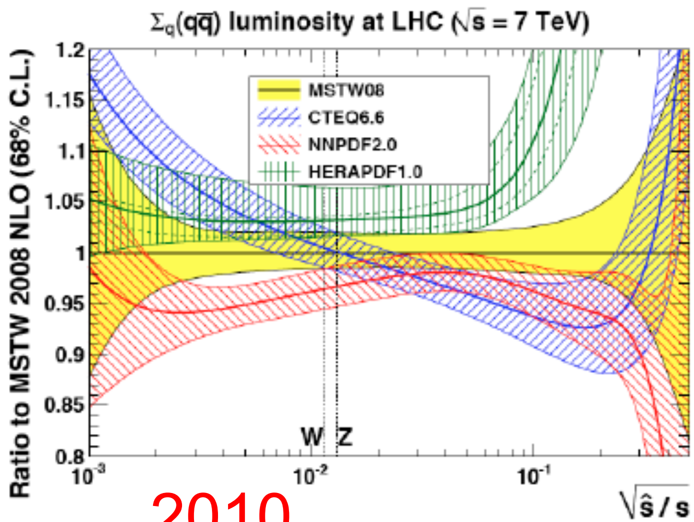
ABM11 systematically larger at small mass, then falls off more rapidly at high mass



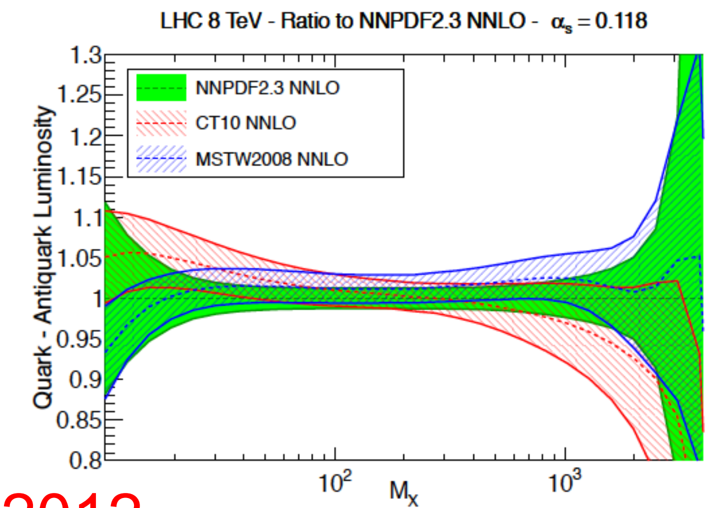


Uncertainties have improved

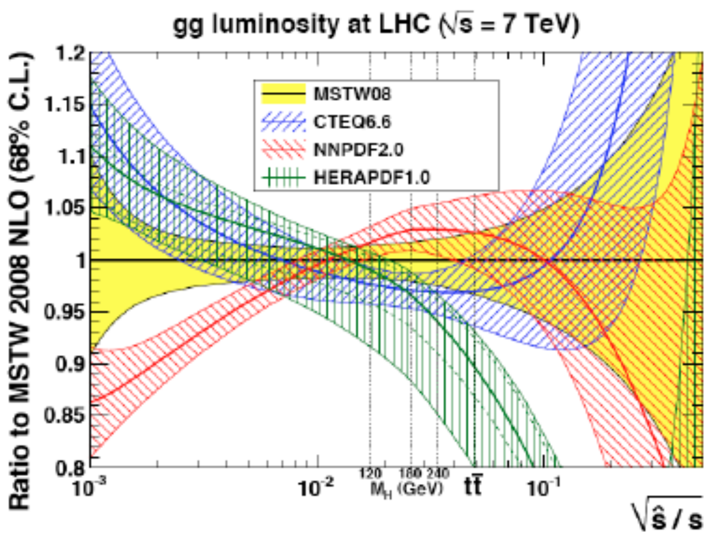
- …with additional data and in going from NLO to NNLO

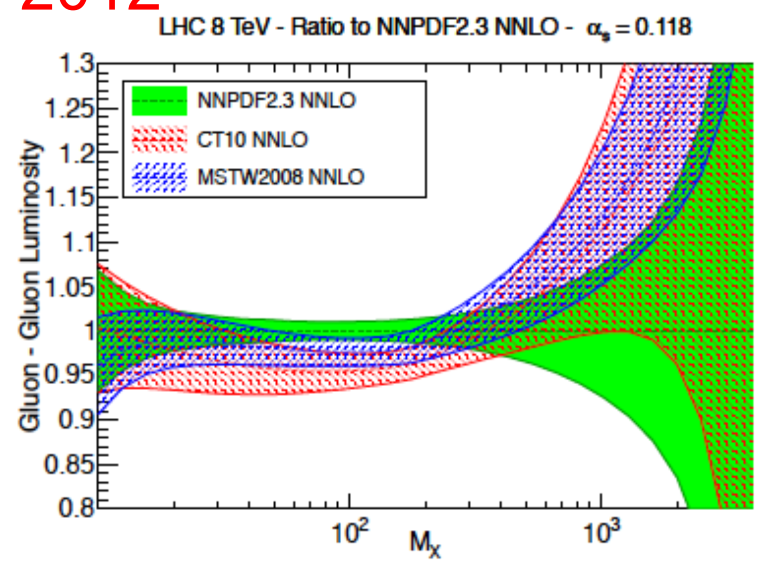


2010

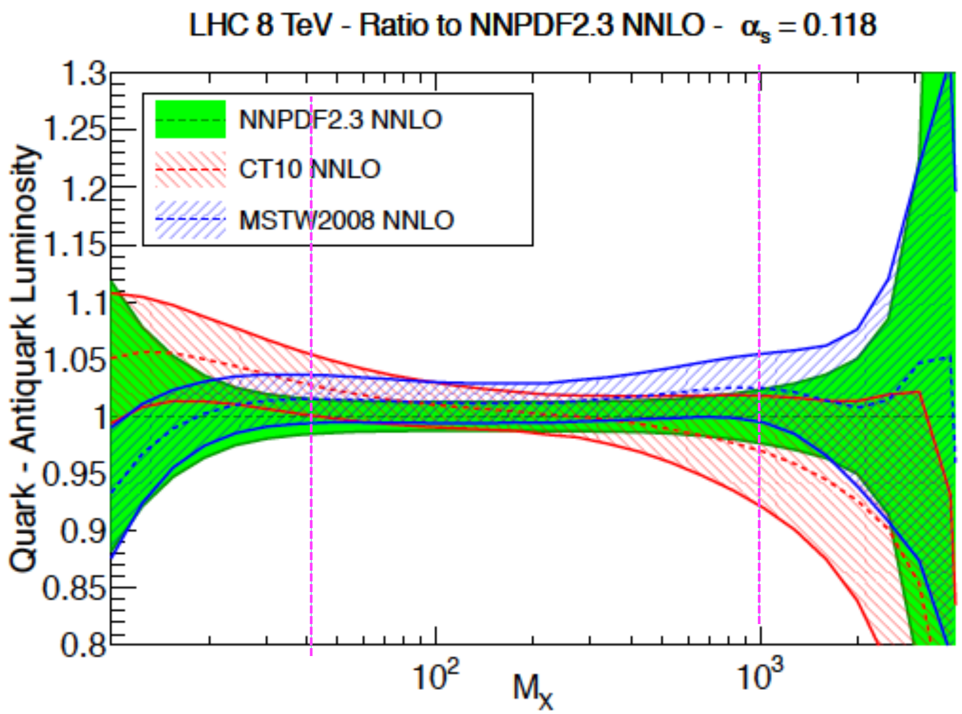


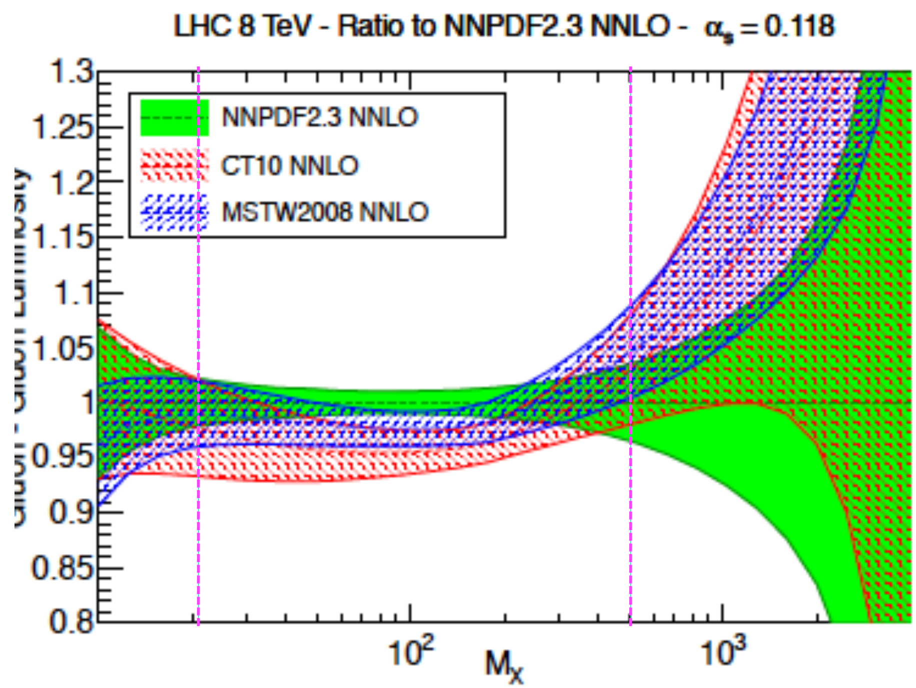
2012





Gallia est omnis divisa in partes tres PDFs sunt





small x region

precision region

discovery region

small x

precision region

discovery region

BSM searches, SM cross sections provide information

Compare relative luminosity uncertainties

good agreement in size of uncertainties between the 3 global PDFs

larger uncertainties of HERAPDF1.5 apparent

ABM11 uncertainties smaller at high mass

note the uncertainties starting to blow up at low mass; low mass x values become moderate mass x values at 100 TeV

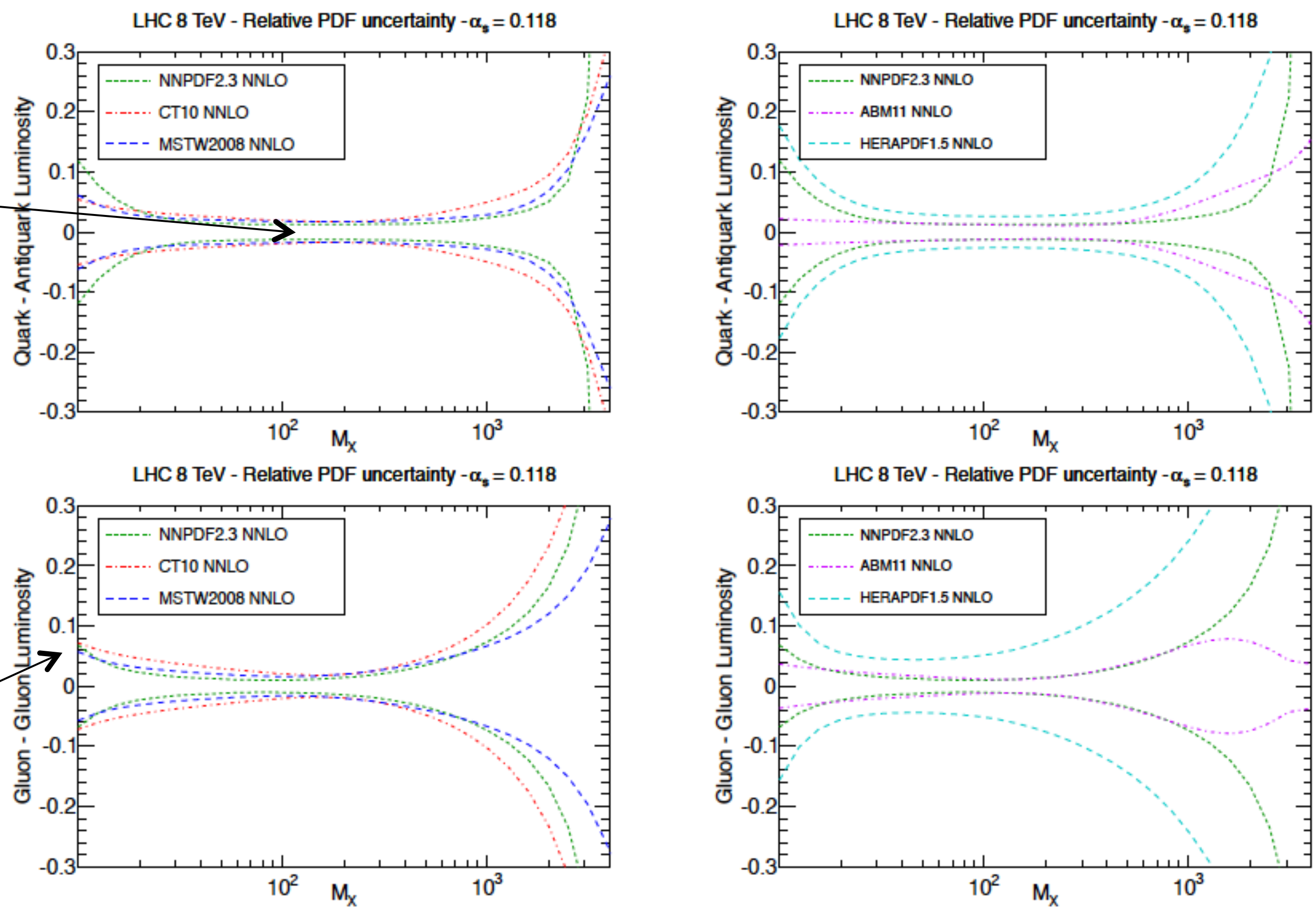
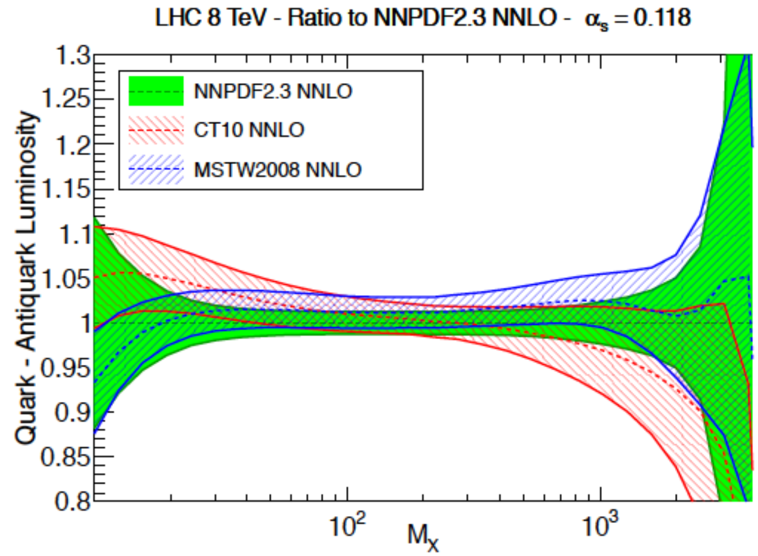
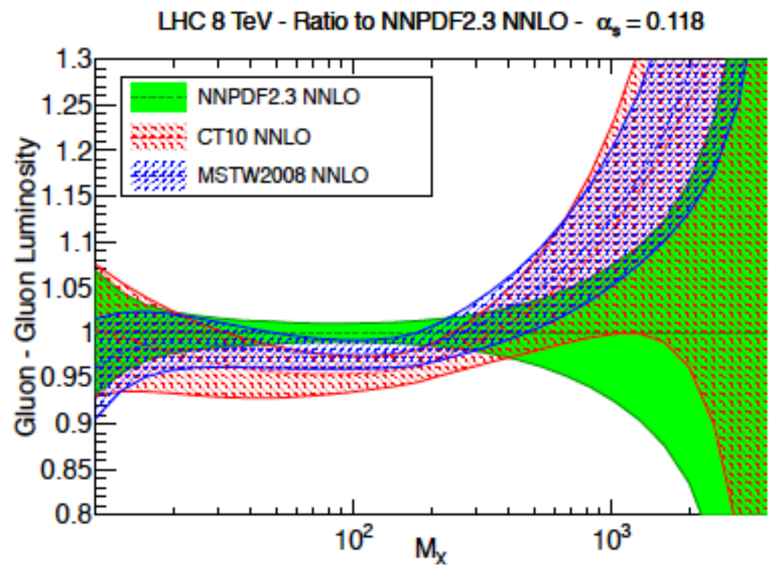


Figure 8: The relative PDF uncertainties in the quark-antiquark luminosity (upper plots) and in the gluon-gluon luminosity (lower plots), for the production of a final state of invariant mass M_X (in GeV) at the LHC 8 TeV. All luminosities are computed at a common value of $\alpha_s = 0.118$.

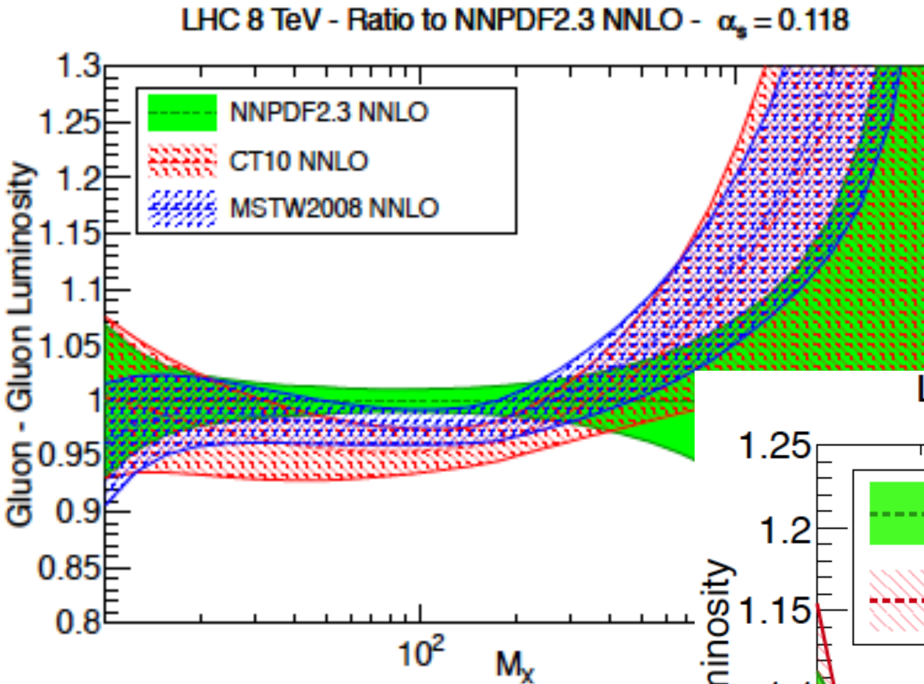
NNLO PDF uncertainties

- Nice convergence for qQ PDF luminosities in range of W/Z masses (at 8 TeV)
  - but not so for lower masses
- Also not so for gg PDF luminosities around 125 GeV at 8 TeV
  - better overlap, but with larger uncertainties, at low mass
  - PDF+α_s error dominant theory error
- Project started at Les Houches
  - understand differences in central luminosity value from CT10, MSTW08, NNPDF2.3 and HERAPDF1.5
  - progress report in Les Houches
  - meetings continuing

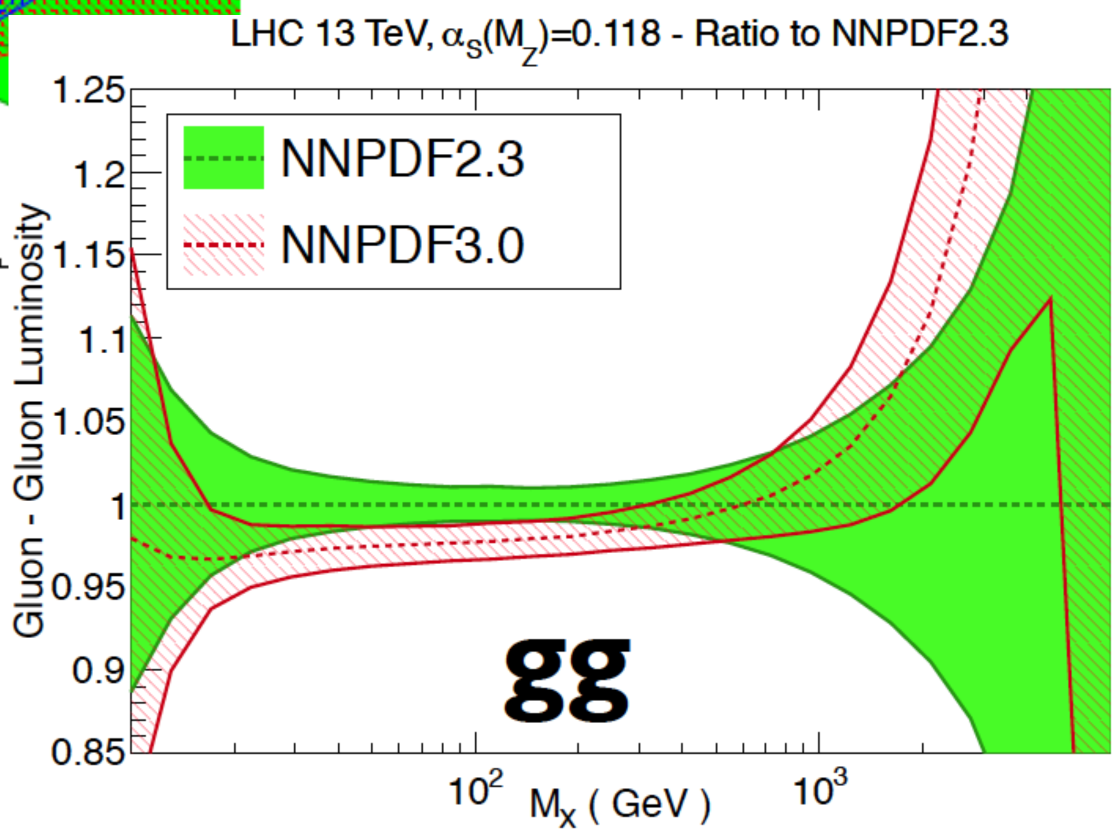




NNLO PDF uncertainties

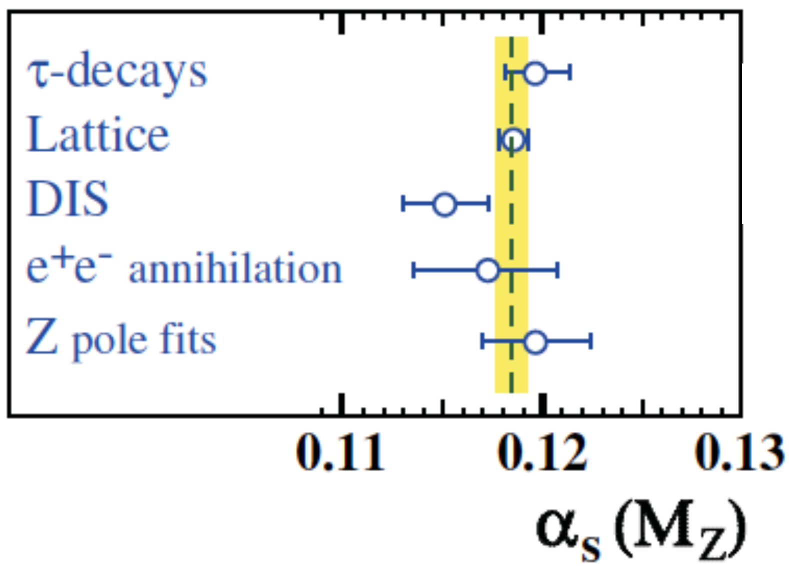


gg PDF luminosity for NNPDF3.0 drops compared to 2.3, so agreement for gg should become similar to that for qQ in new comparisons



$\alpha_s(m_Z)$

- Right now the Higgs Cross Section Working Group is using a mean value for $\alpha_s(m_Z)$ of 0.118 with 90% CL error of 0.002 (68%CL error of 0.012), or an inflation of the world average uncertainties; the α_s error is added in quadrature with the PDF error
- The world average is dominated by lattice results
- Are the lattice results are robust enough, so that an uncertainty of 0.012 (at 68% CL) may be an overestimate? Will the uncertainty in α_s be a non-issue at the time of any 100 TeV collider



variety of different calculations/groups results in very compatible results

Figure 1-1. *Summary of values of $\alpha_s(M_Z^2)$ obtained for various sub-classes of measurements. The world average value of $\alpha_s(M_Z^2) = 0.1184 \pm 0.0007$ is indicated by the dashed line and the shaded band. Figure taken from [1].*

Update of recommendation

- Use updated versions of PDFs present in the old recommendations
  - CTEQ6.6->CT10
  - MSTW08->MSTW08
  - NNPDF2.1->NNPDF2.3
- Use central value of $\alpha_s(m_Z)$=0.118 for each set
- PDF uncertainty (at NLO and NNLO) given by envelope of these three sets
- α_s error given by variation of +/-0.0012 around central value of 0.118
- Add PDF + α_s errors in quadrature

New PDF4LHC exercise

- Lay out a coherent coordinated plan for QCD(+EW) measurements, among ATLAS, CMS and LHCb, that can reduce PDF systematics using LHC data
  - again systematic errors will be very important
  - and the LHC is competing against high precision HERA data (as well as high precision fixed target DIS/DY data)
  - most of contribution of precision may be to ‘discovery region’
- Wiki is now up

https://twiki.cern.ch/twiki/bin/view/PDF4LHC/WebHome

…but, arXiv:1407.7031

- One of those important LHC cross sections is inclusive jet production; but it's only known to NLO (NNLO for gg initial state)
- NNLO/NLO corrections smaller (on the order of 5%) and flat as a function of jet p_T if scale of inclusive jet pT is used rather than p_T of the lead jet
- …which is what should be used in any case
- expect corrections for other subprocesses to be of similar order

Casimir for biggest color representation final state can be in

Simplistic rule

$C_{i1} + C_{i2} - C_{f,max}$

L. Dixon

Casimir color factors for initial state

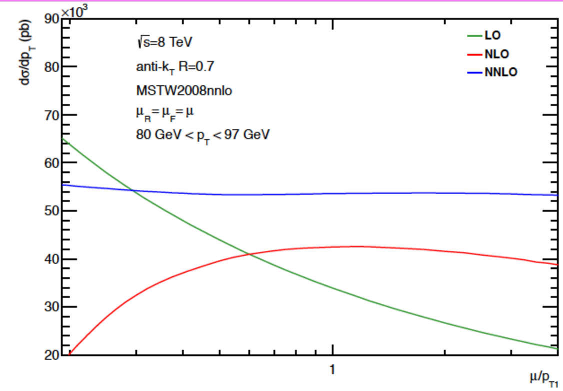


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

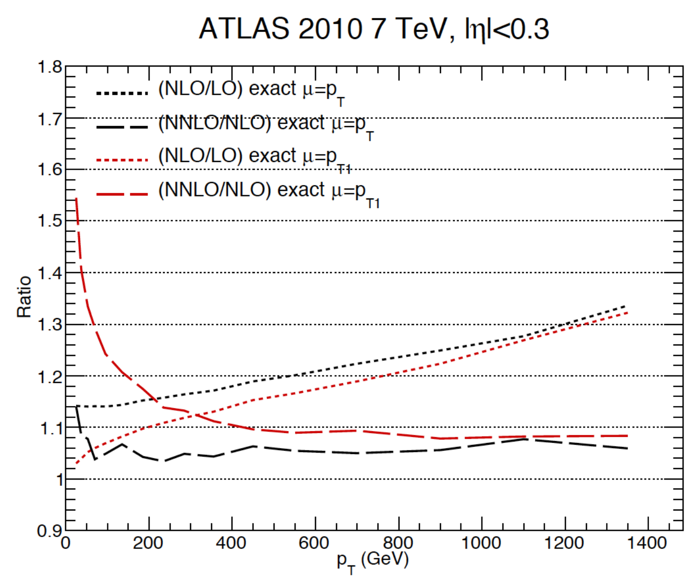


Figure 8: NLO/LO and NNLO/NLO exact k-factors for the gg-channel evaluated with the renormalisation and factorisation scales $\mu_R = \mu_F = p_T$ and $\mu_R = \mu_F = p_{T1}$.

On to 100 TeV

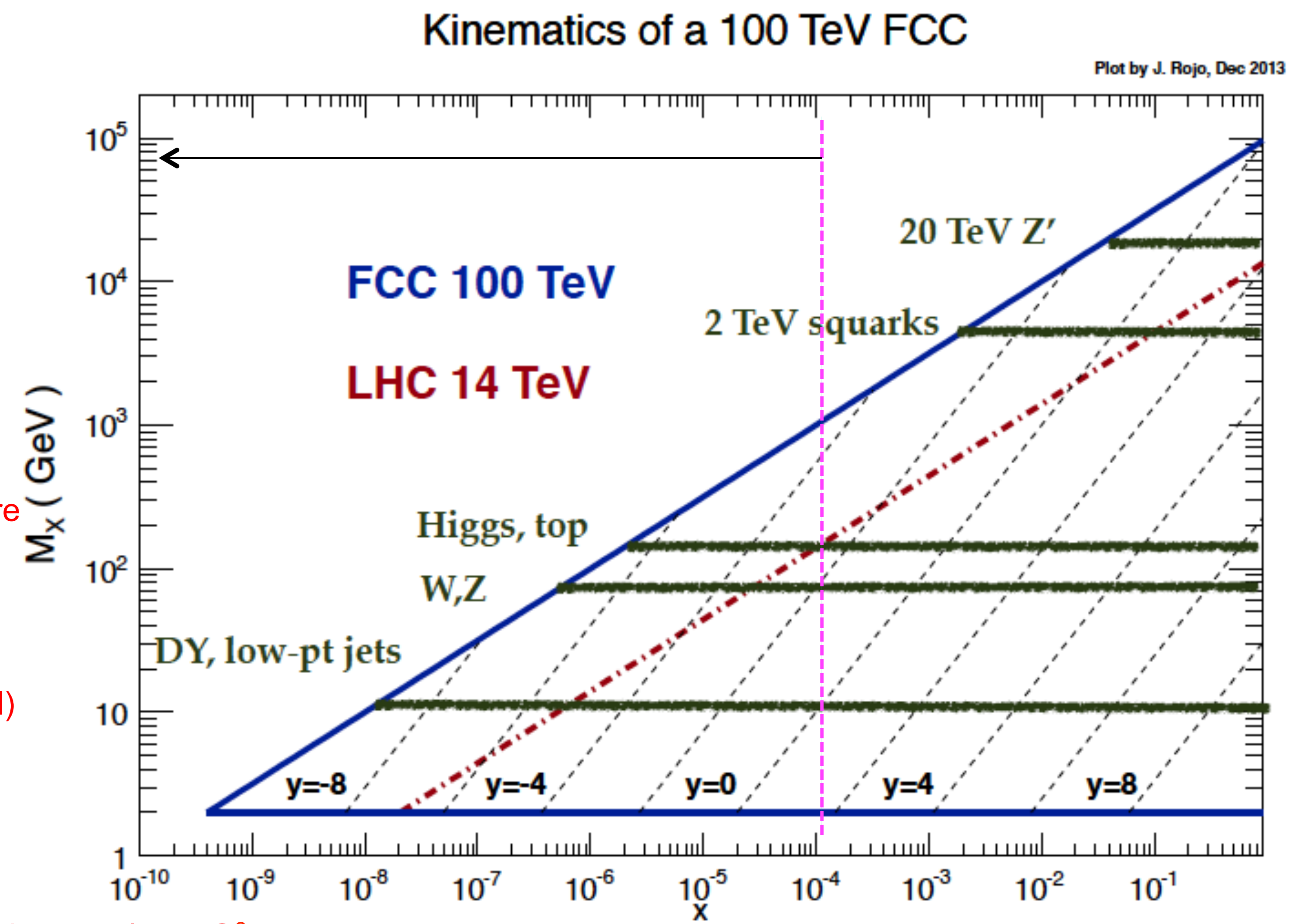
will access smaller x, larger Q^2

currently have no constraints on PDFs for x values below 1E-4

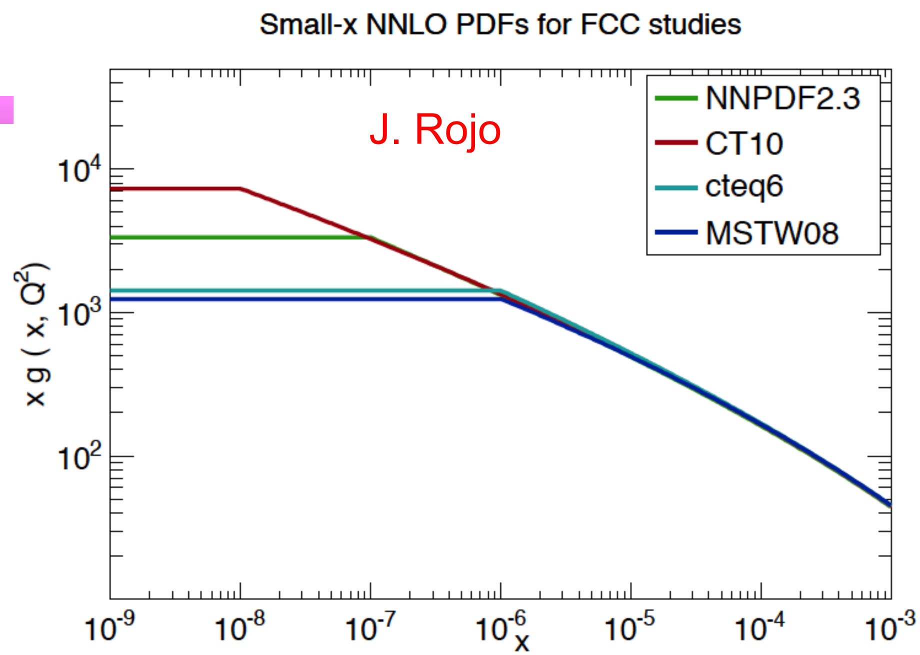
we don't know where at low x BFKL effects start to become important

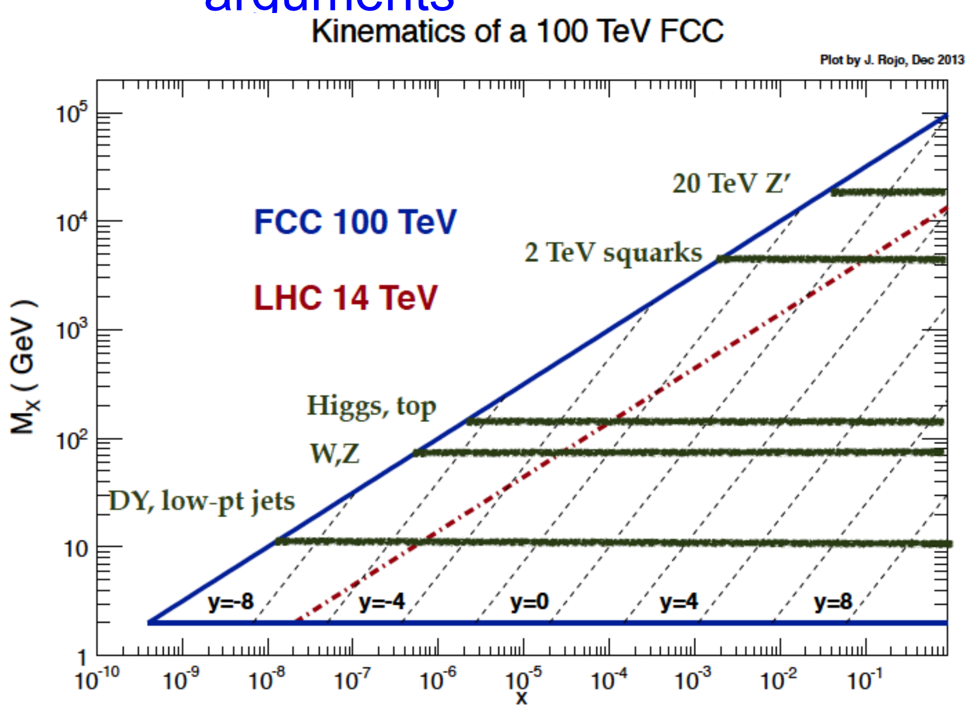
poor constaints (still) as well for high x PDFs

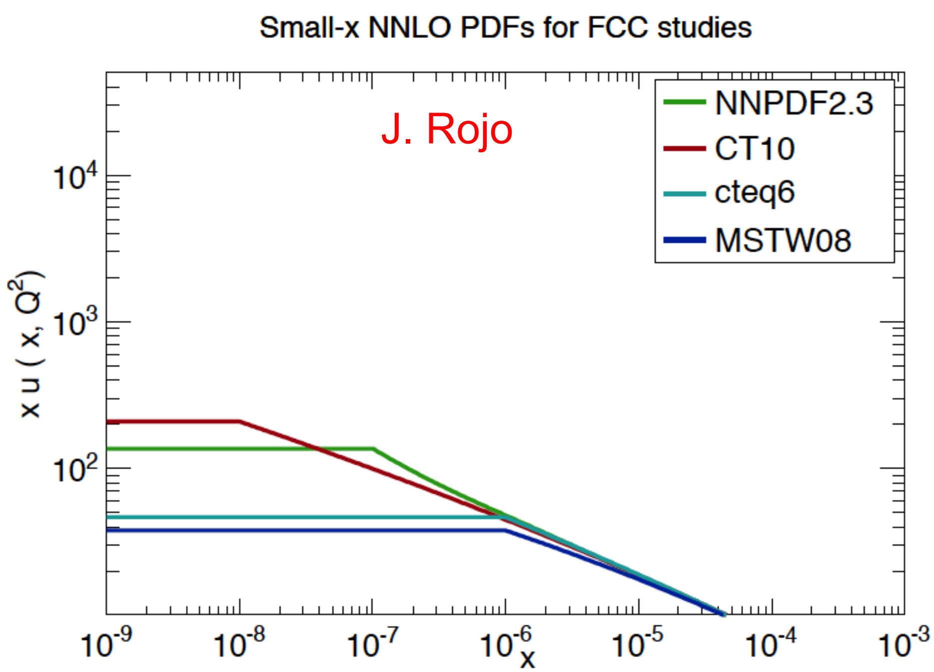
at high masses (Q^2), rely on DLAP evolution; we know at large Q^2, EW effects also become important



- Information for PDFs below x value of 1E-4 very sparse
- Most current PDFs cut off at some low x value
- Can extrapolate, but it is just that, extrapolation, perhaps based on some Regge arguments

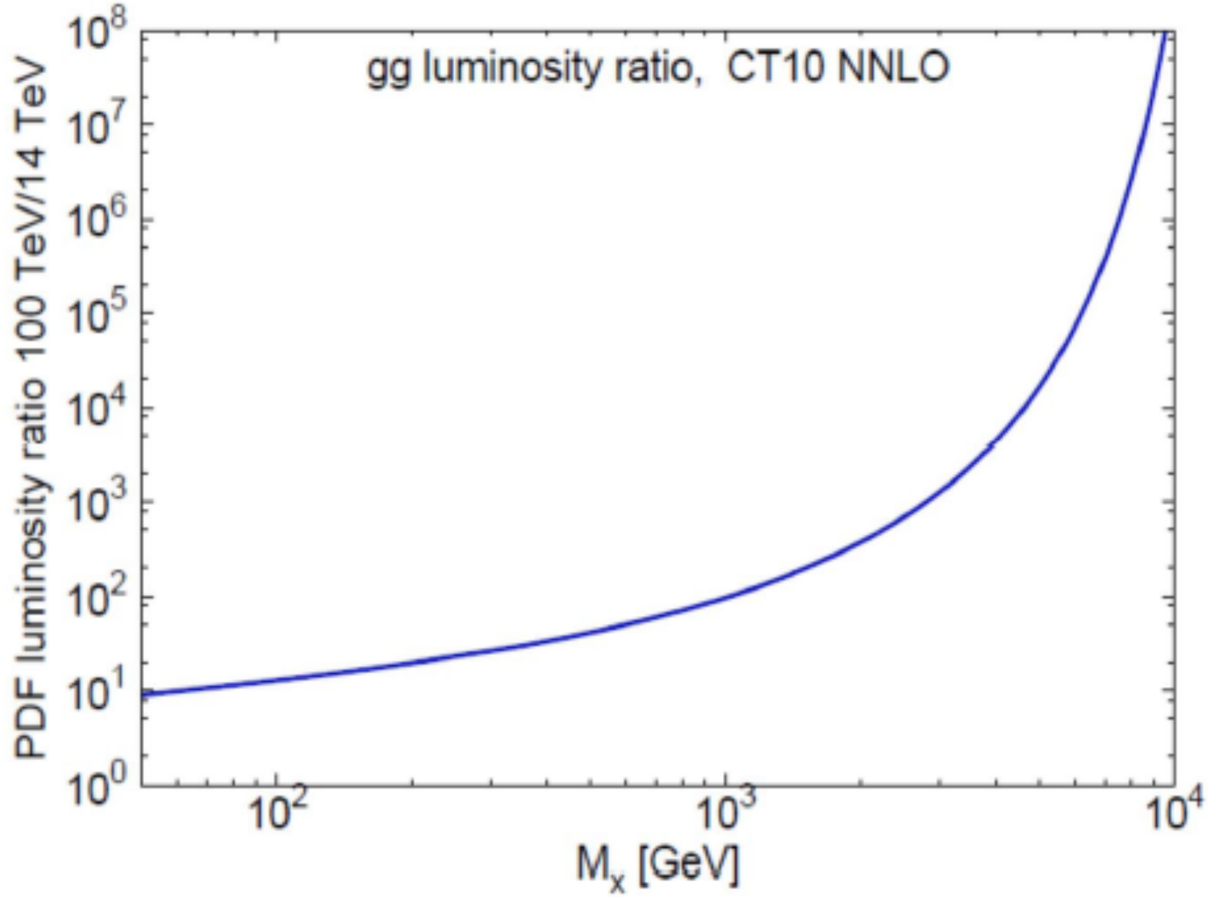






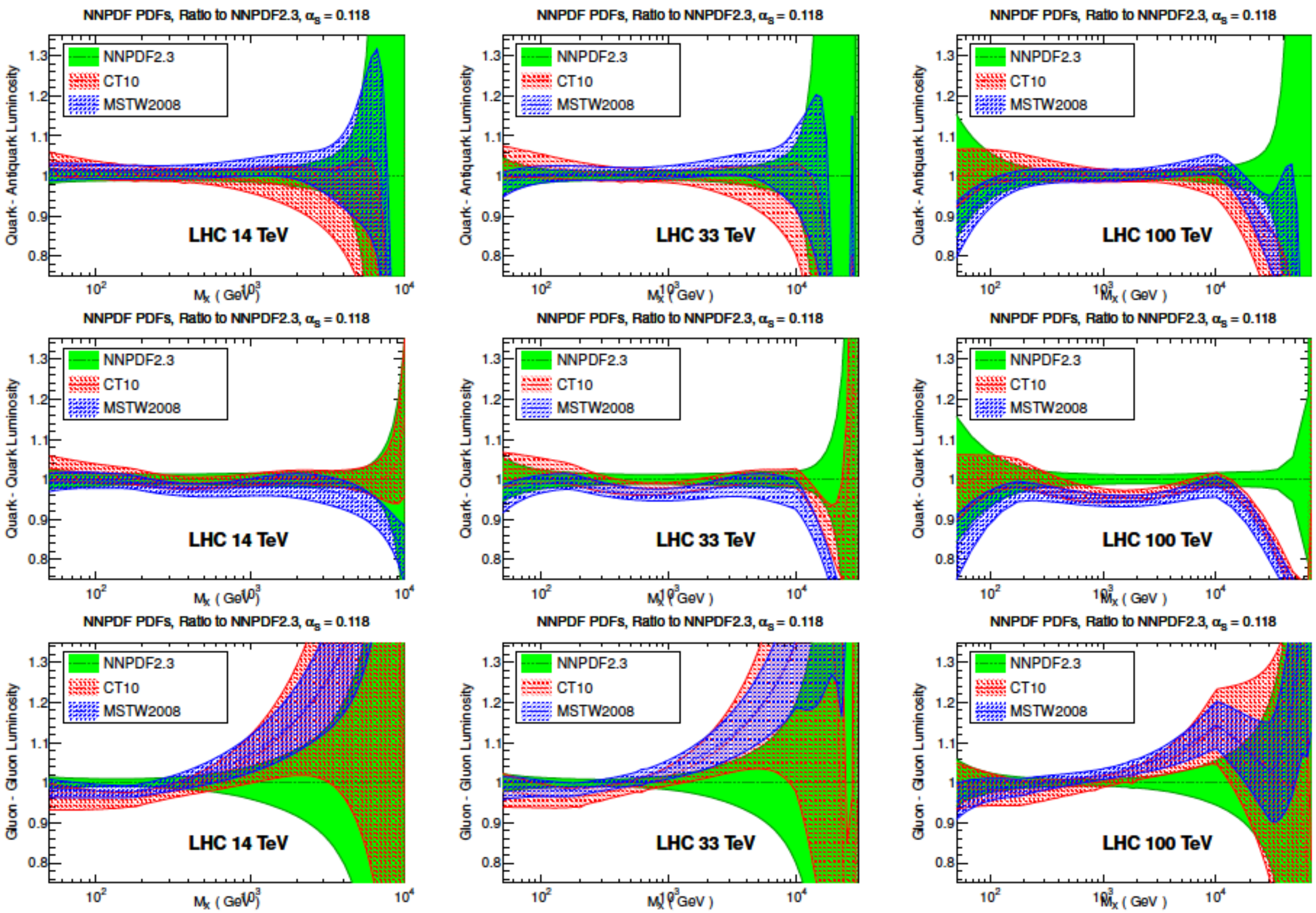
PDF luminosities at 100 TeV

- gg luminosity ratio at order of 100 at TeV scale 1E8 at 10 TeV scale
- Similar increases for other PDFs



PDFs at higher energies: as part of the Snowmass exercise

PDFs are HERA/fixed target dominated for x<~0.05-0.1; LHC data at 14 TeV offers opportunity for shrinking uncertainties in new physics search range

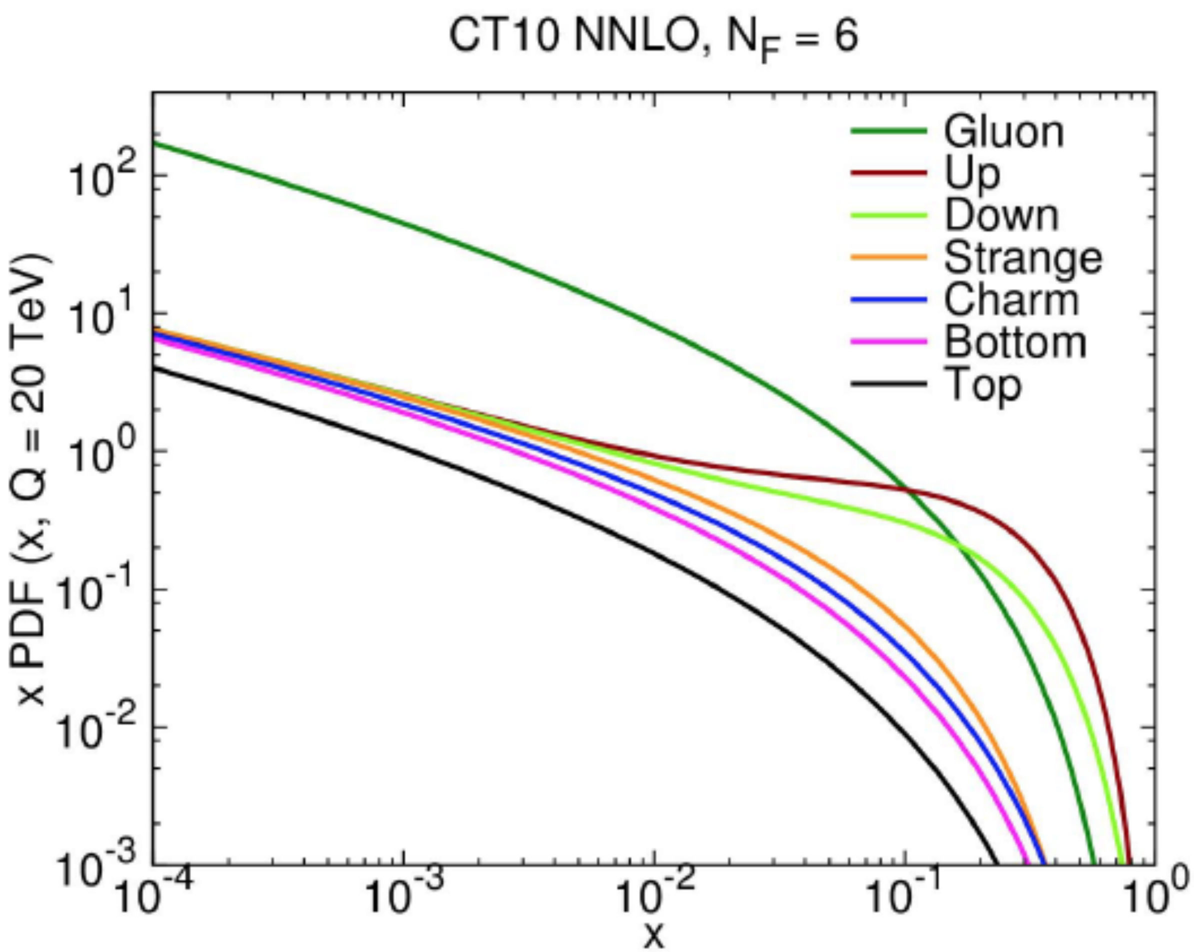


high masses always a problem, with current uncer-tainties

low masses become a problem at very high energy colliders

Top quark PDFs

CT10 Top PDFs
(Q=20 TeV)

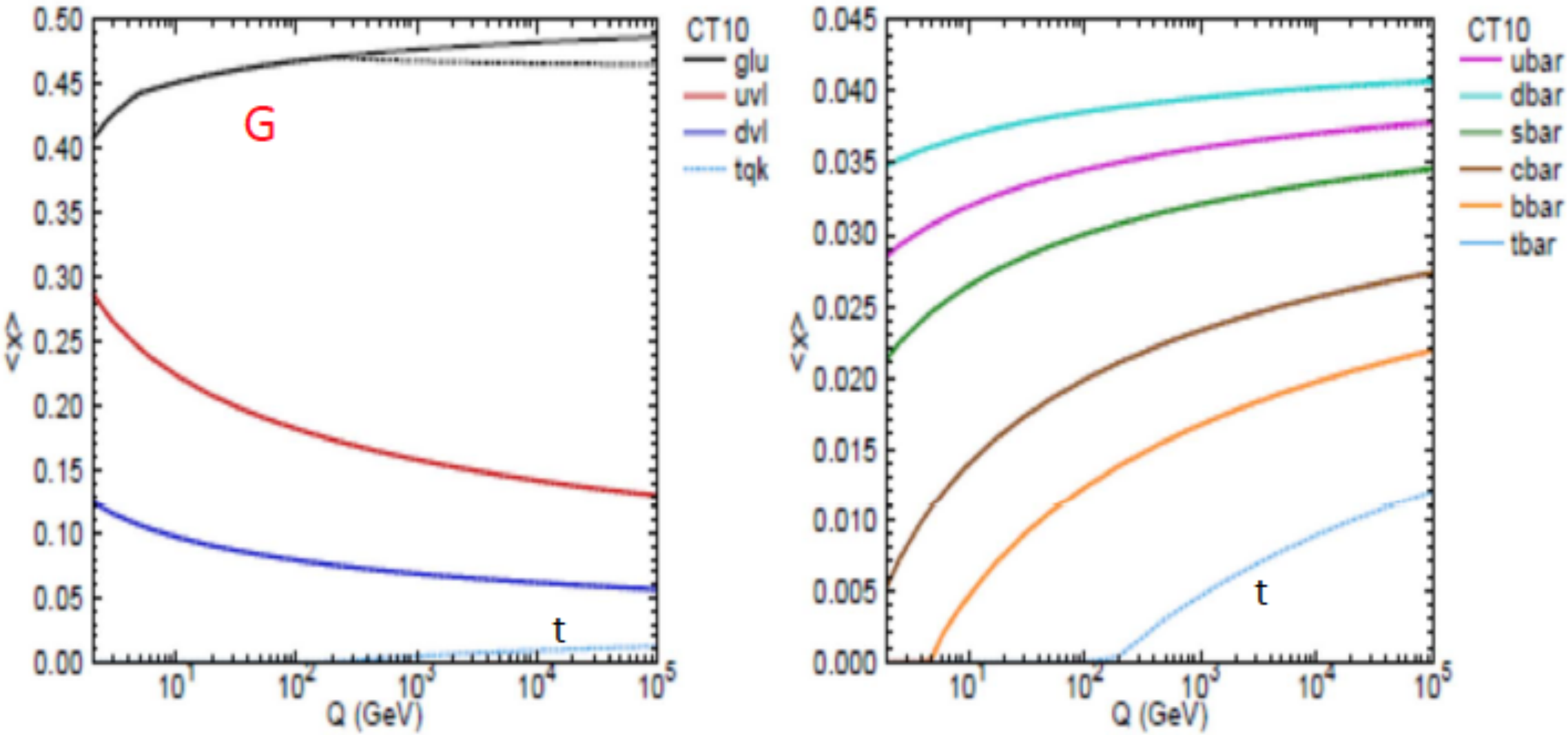


- At very high Q^2, top mass becomes small, and top PDFs may need to be taken into account

see talk of
Ismail Ahmed

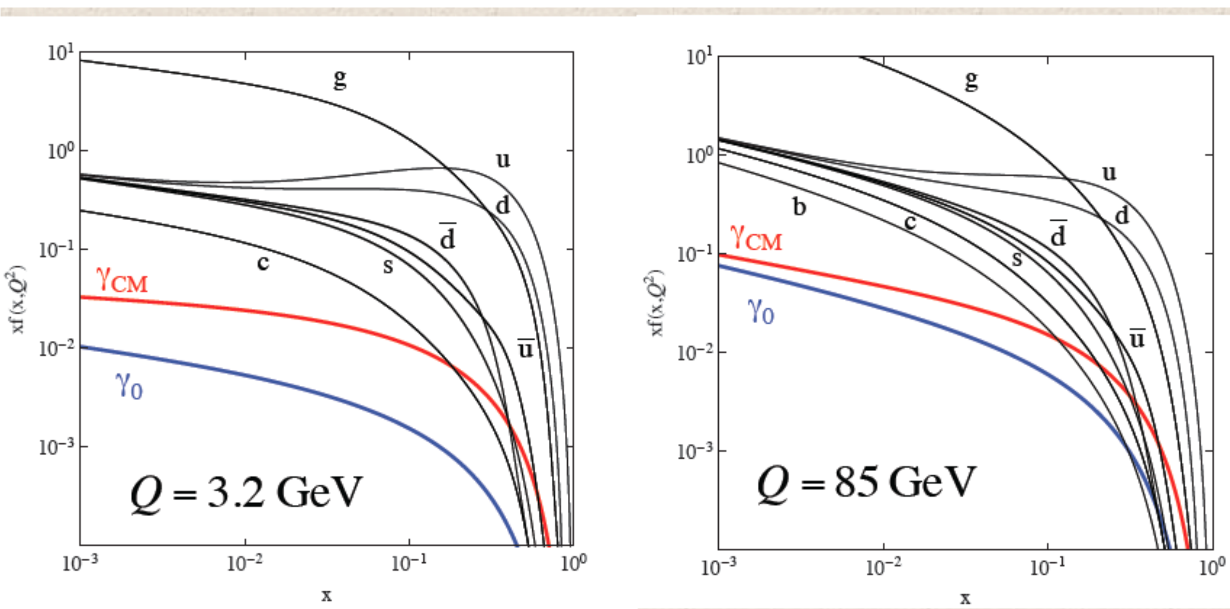
Top takes some of gluon momentum

Momentum fraction inside proton



Photon PDFs

- Photon PDFs: photon PDFs can be larger than antiquark distributions at high x; the LHC is a γγ collider; even more true of a 100 TeV collider
- NNPDF has developed photon PDFs + QED corrections (in addition to MRST2004QED)
- CT10 in progress (see talk of C. Schmidt at DIS2014)
    - fitting to photon production in DIS



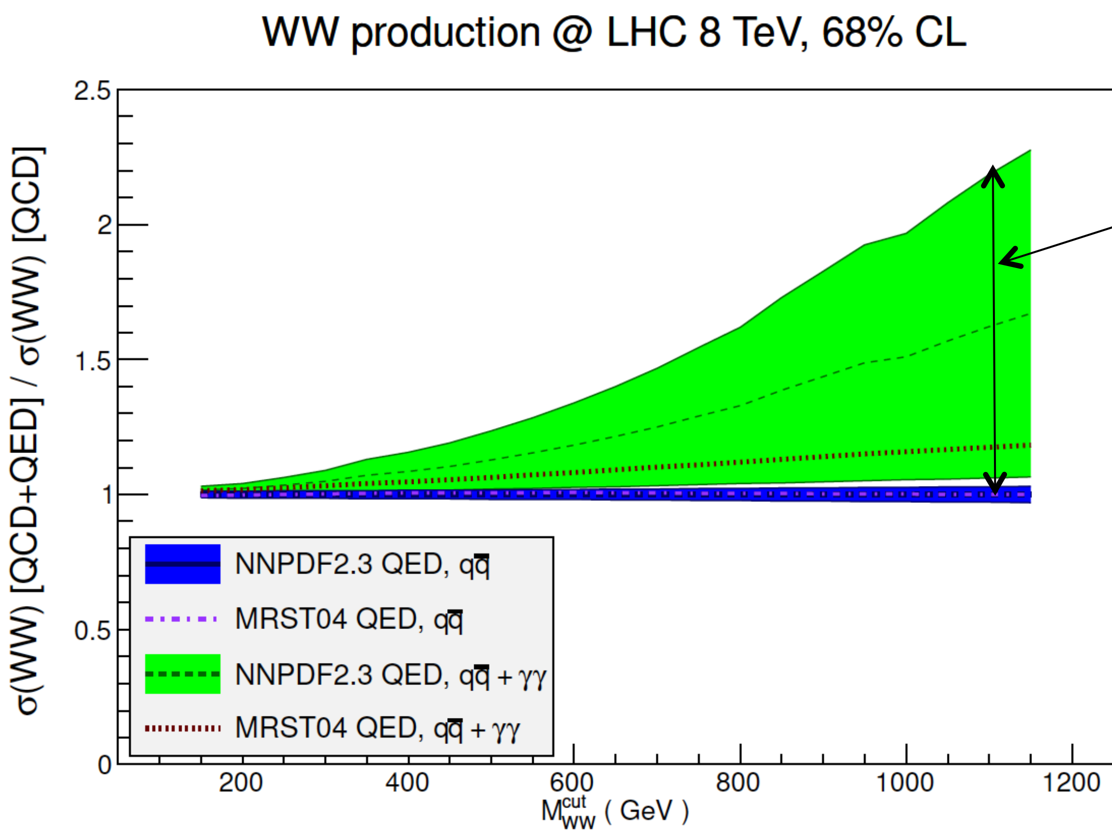
γ momentum fraction:

$p^{\gamma}(Q)$	$\gamma(x,Q_0)=0$	$\gamma(x,Q_0)_{CM}$
$Q = 3.2$ GeV	0.05%	0.34%
$Q = 85$ GeV	0.22%	0.51%

allow for non-perturbative component of photon at Q_o

WW production and the photon PDF

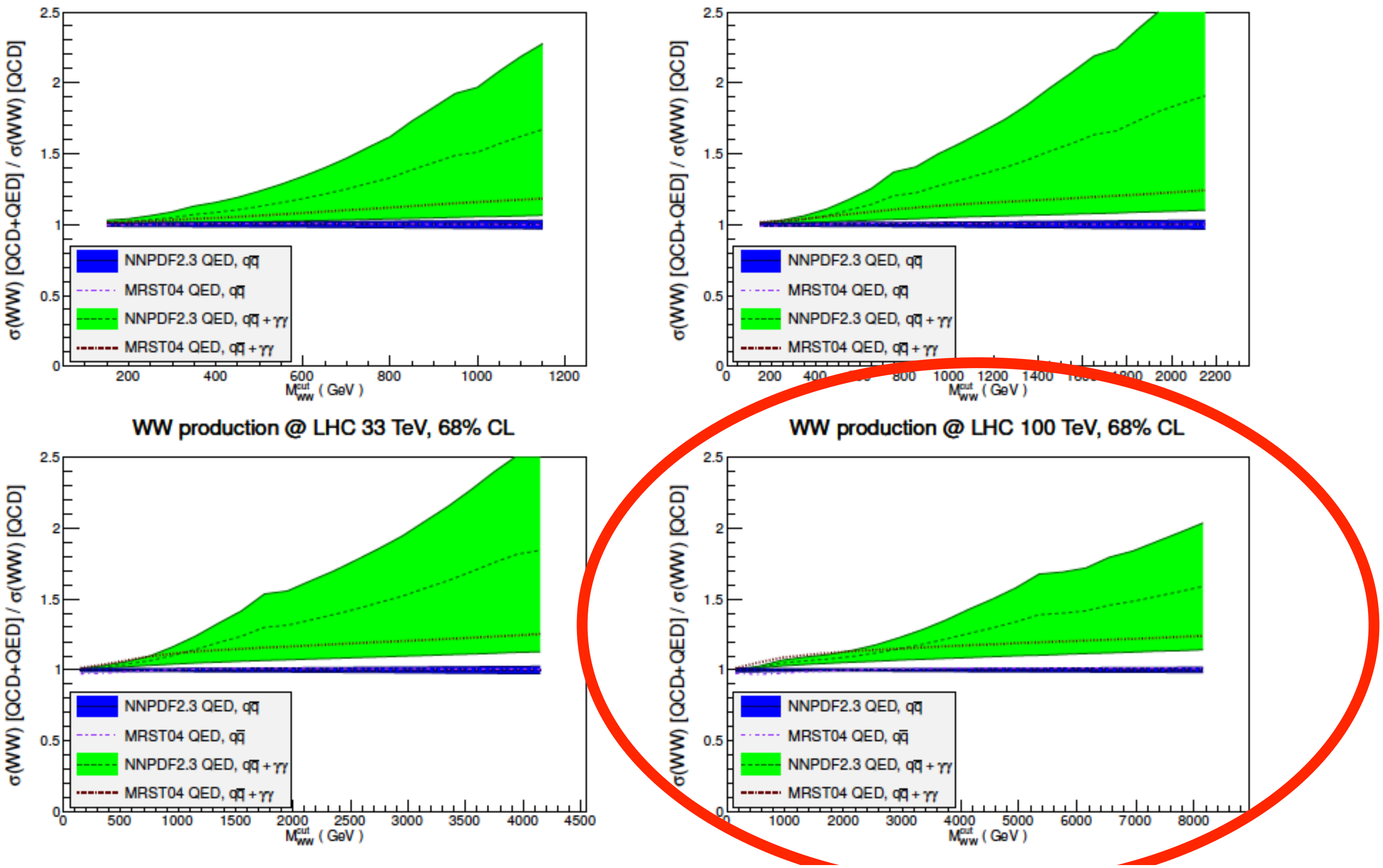
- photon-induced WW production can contribute significantly at high mass
- …and understanding high mass WW production will be important in the next run
- a better understanding of the photon PDF is thus crucial
  - first steps taken with LHC DY data



with currently a very large uncertainty due to lack of knowledge of the photon PDF

QED corrections

- Photon PDFs will become important as energies increase for processes such as $\gamma\gamma$->WW

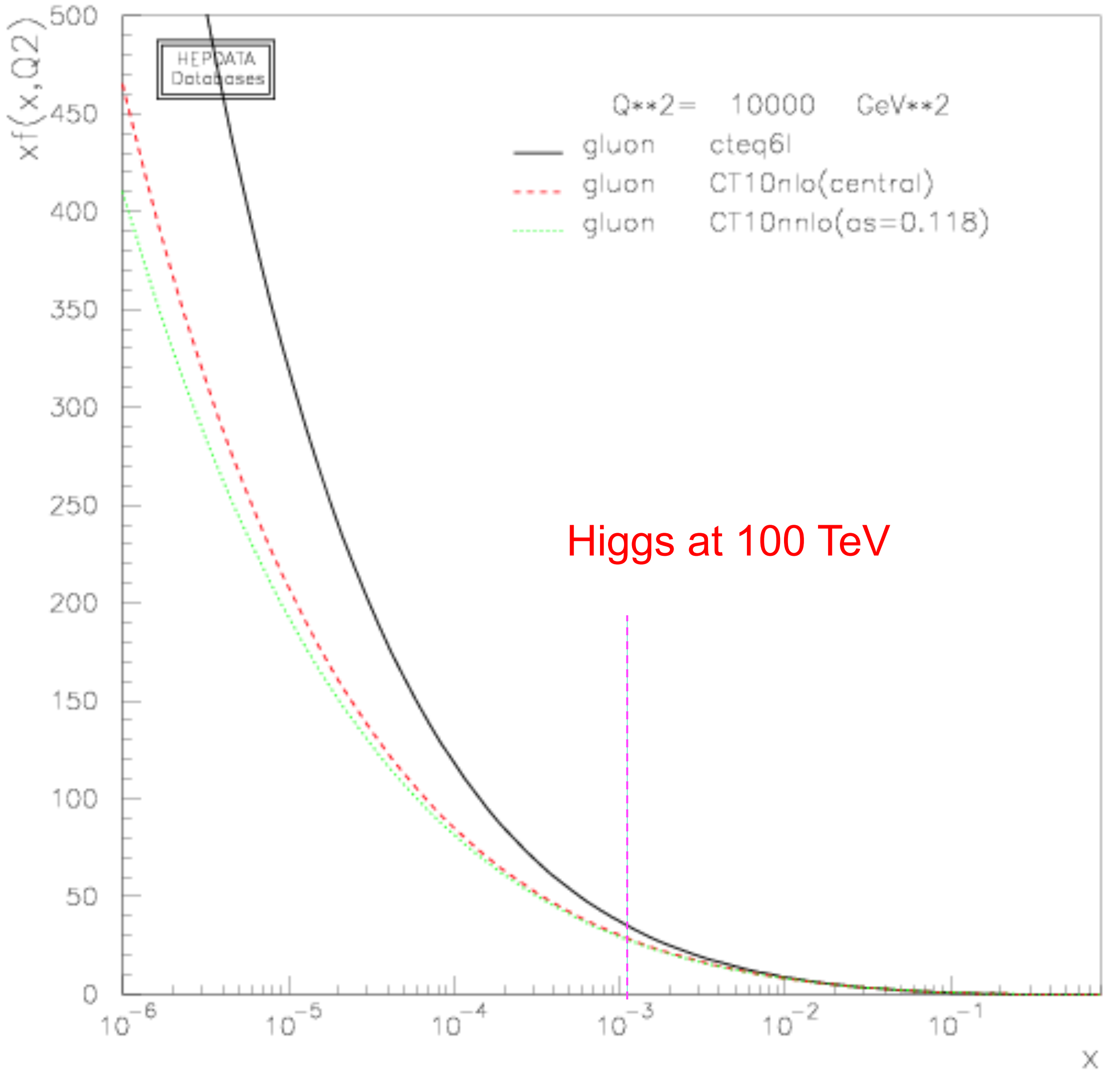


EW corrections

- At high Q^2, logs of $\alpha \ln(Q^2/m_W{}^2)$ become large; EW corrections become as large as higher order QCD corrections
- Need EW evolution for PDFs
  - W and Z PDFs
  - Ciafaloni and Comelli, 2002, 2005
- …in Les Houches proceedings, a *dictionary* for QCD+EW corrections has been provided by Stefan Dittmaier

Will we need N^{3}LO PDFs for 100 TeV?

- There's a big change in the gluon distribution in going from LO to NLO
- Much smaller change from NLO to NNLO
- In Higgs kinematic region, scale uncertainties will dominate over PDF order effects
  - Forte, Isgro and Vita, arXiv: 1312.6688
- Maybe for precision physics at smaller x?



Meta-PDFs:arXiv:1401.0013

- Take NNLO PDFs (or NLO PDFs)

NNLO	Initial scale	α_S	Error type	Error sets
CT10	1.3	0.118	Hessian	50
MSTW'08	1.0	0.1171	Hessian	40
NNPDF2.3	1.414	0.118	MC	100

- Choose a meta-parametrizaton of PDFs at initial scale of 8 GeV (away from thresholds) for 9 PDF flavors (66 parameters in total)

$$f(x, Q_0; \{a\}) = e^{a_1} x^{a_2} (1-x)^{a_3} e^{\sum_{i\geq 4} a_i \left[T_{i-3}(y(x))-1\right]}$$

- Generate MC replicas for all 3 groups and merge with equal weights, finding meta parameters for each of the replicas by fitting PDFs in x ranges probed at LHC
- Construct 50 eigenvectors using Hessian method (throw 16 away)
- These 50 eigenvectors provide a very good representation of the PDF uncertainties for all of the 3 PDF error families above

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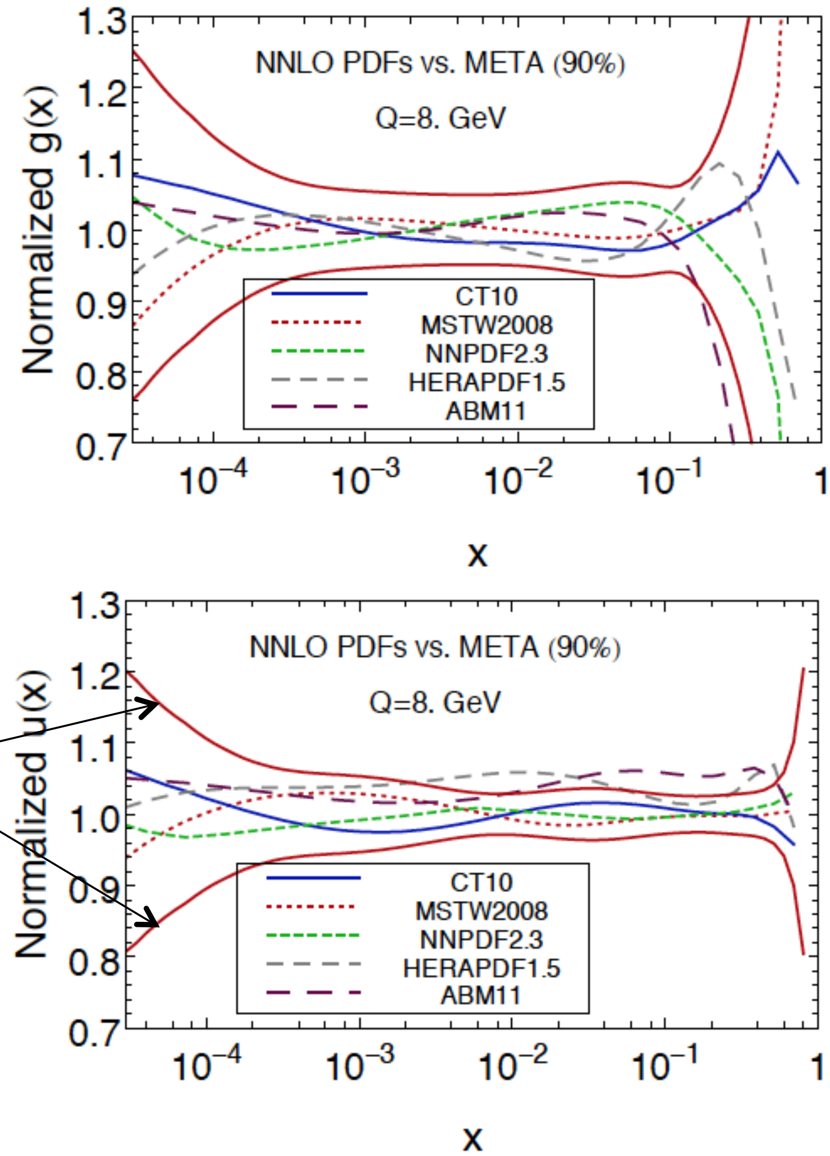
meta-PDFs

- The meta-PDFs provide both an average of the chosen PDFs, as well as a good estimation of the total PDF uncertainty

meta-PDF uncertainty band



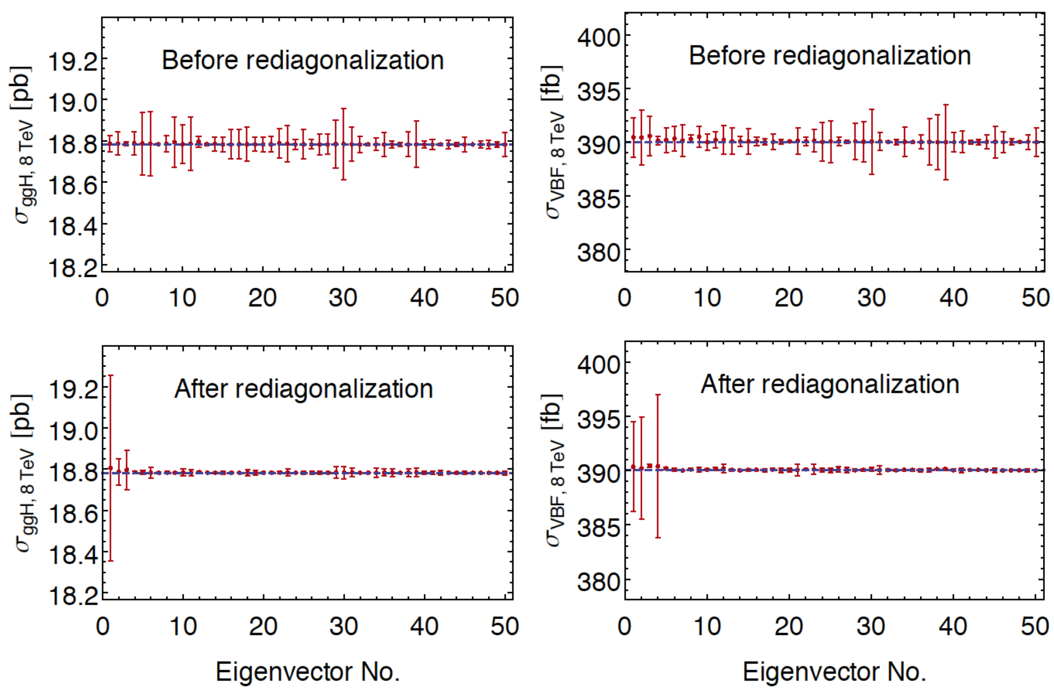
Higgs observables

- Select global set of Higgs cross sections at 8 and 14 TeV (46 observables in total; more can be easily added if there is motivation)

production channel	$\sigma(inc.)$	$\sigma(\lvert y_H\rvert > 1)$	$\sigma(p_{T,H} > m_H)$	scales
$gg \to H$	iHixs1.3 [32] at NNLO	MCFM6.3 [33] at LO	—	m_H
$b\bar{b} \to H$	iHixs at NNLO	—	—	m_H
VBF	VBFNLO2.6 [34] at NLO	same	same	m_W
HZ	VHNNLO1.2 [35] at NNLO	CompHEP4.5 [36] at LO	CompHEP at LO	$m_Z + m_H$
$HW^\pm$	VHNNLO at NNLO	—	—	$m_W + m_H$
HW^+	CompHEP at LO	same	same	$m_W + m_H$
HW^-	CompHEP at LO	same	same	$m_W + m_H$
$H + 1jet$	MCFM at LO	same	same	m_H
$Ht\bar{t}$	MCFM at LO	CompHEP at LO	CompHEP at LO	$2m_t + m_H$
HH	Hpair [37] at NLO	—	—	$2m_H$

Data set diagonalization (arXiv:0904.2424)

- There are 50 eigenvectors, but can re-diagonalize the Hessian matrix to pick out directions important for the Higgs observables listed on previous page; with rotation of basis, 50 eigenvectors become 6



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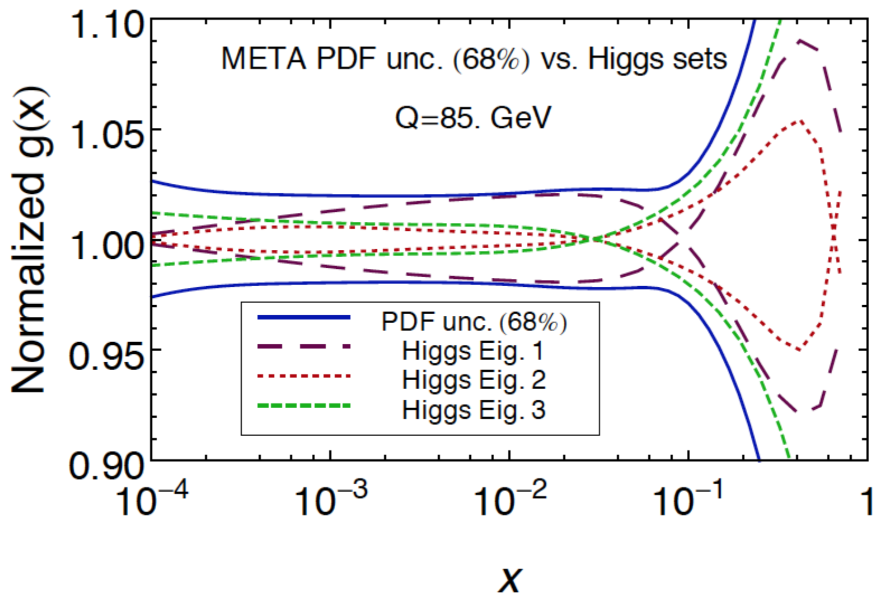
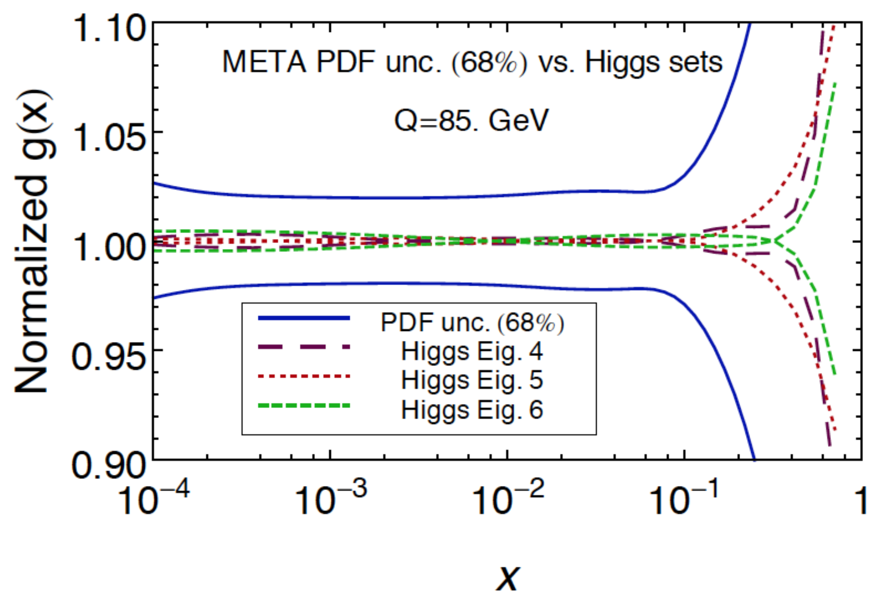
(in progress)

It's possible to define a few eigenvectors which completely encompass the PDF and α_s uncertainties for CT10, MSTW08 and NNPDF2.3 for Higgs production for 8-14 TeV; no reason this cannot be expanded to 100 TeV

Re-diagonalized eigenvectors

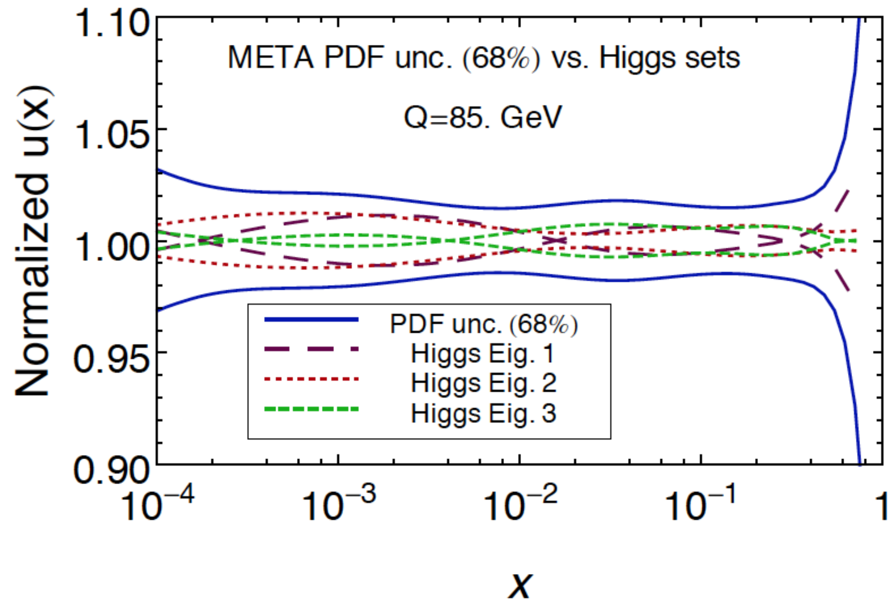
- Eigenvectors 1-3 cover the gluon uncertainty
- Note that eigenvector 1 saturates the uncertainty for most of the gg->Higgs range

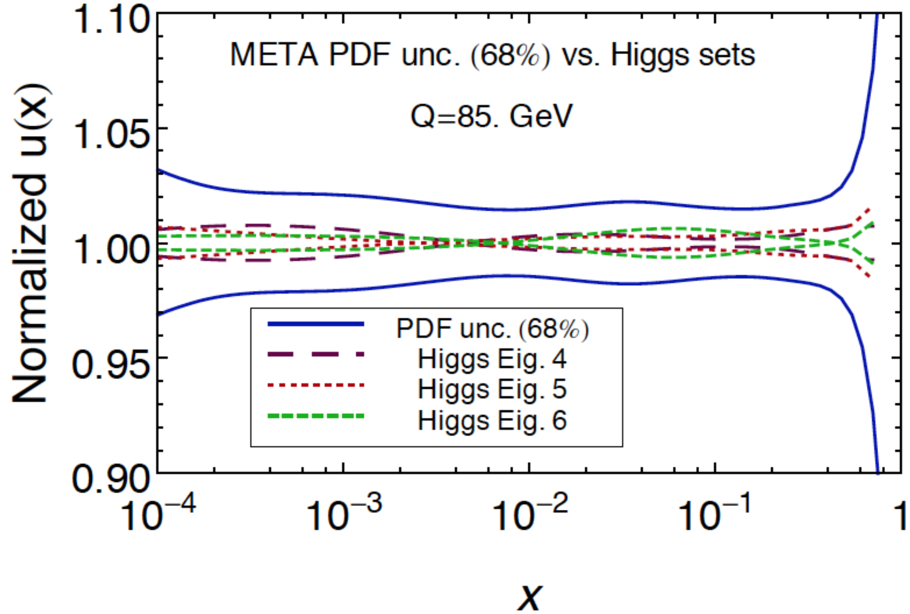




Re-diagonalized eigenvectors

- Up quark uncertainties a bit more distributed





arXiv:1004.4624

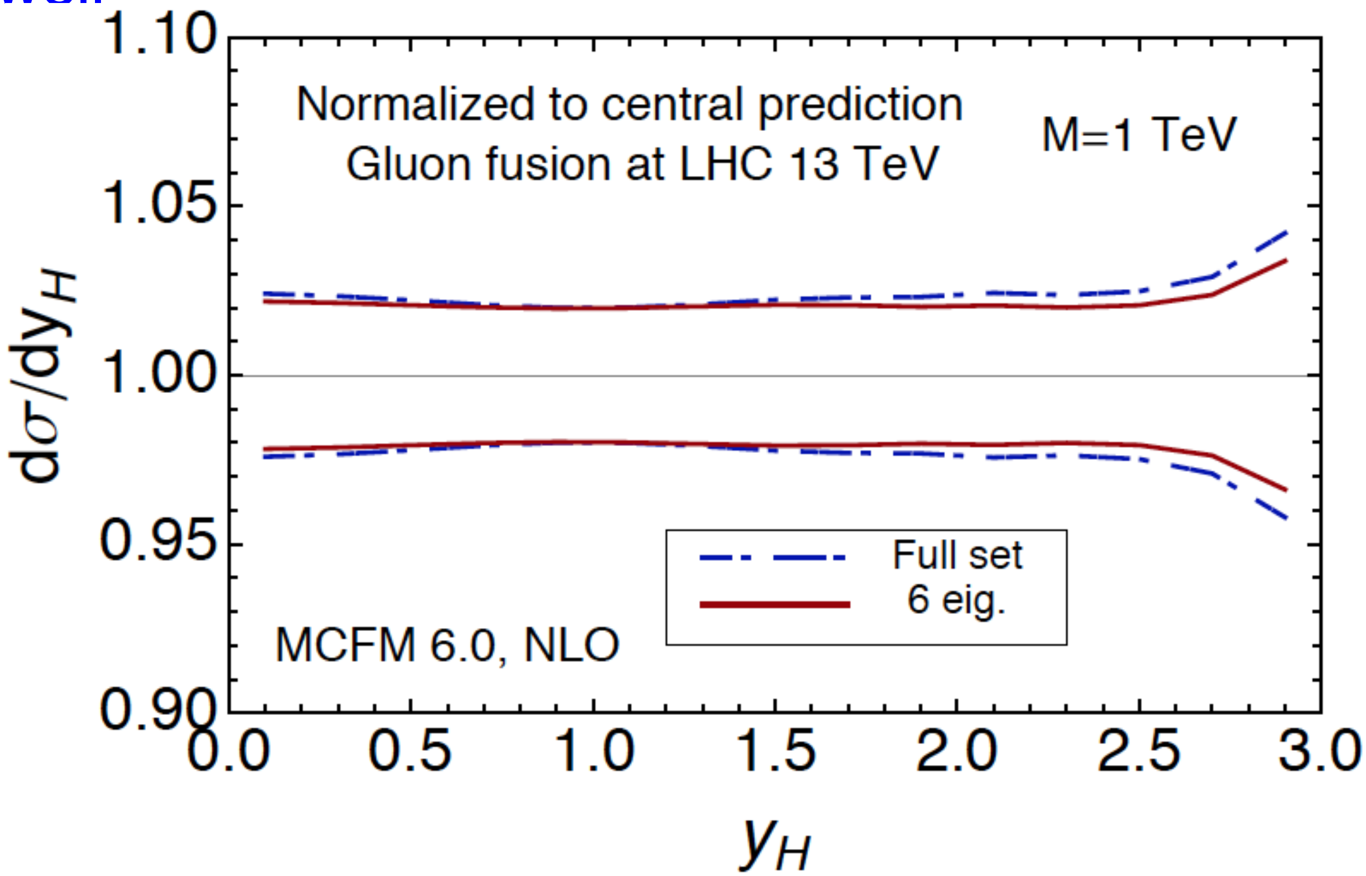
- Treat α_s input as another eigenvector; α_s and PDF uncertainties can be added in quadrature ($\alpha_s(m_Z)$=0.118+/0.0012)
- So 7 eigenvectors to represent all PDF+α_s uncertainty

LHC	$\Delta\alpha_s(M_Z)$	GGH inc.	GGH $0j$ exc.	GGH $1j$ exc.	GGH $2j$ inc.	VBF inc.
LHC 8 TeV	$+1\sigma$	2.2%	1.6%	3.0%	4.8%	-0.23%
	-1σ	-2.2%	-1.6%	-2.8%	-4.8%	0.11%
LHC 14 TeV	$+1\sigma$	2.1%	1.4%	2.6%	4.5%	0.05%
	-1σ	-2.0%	-1.4%	-2.5%	-4.4%	-0.09%

❖ using PDF α_s series of the META PDFs

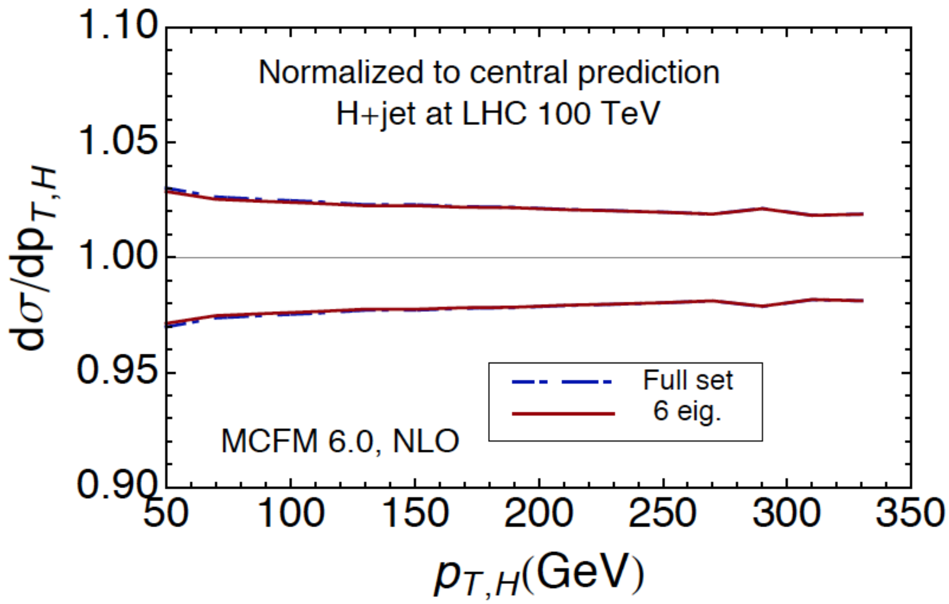
Try other distributions

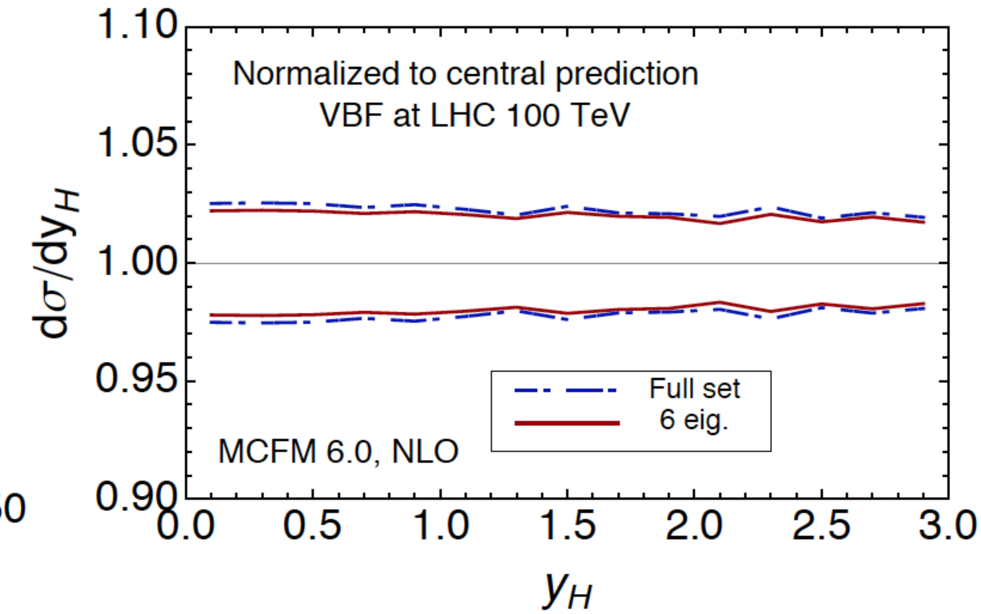
- Look at rapidity distribution for production of a 1 TeV mass state through gg fusion
- This was not an input to the re-diagonalization, but still works fairly well



Look at 100 TeV

- Again, these cross sections were not used in the re-diagonalization





Summary

- In general, good agreement among global PDF sets for LHC predictions
  - gg initial states not as good, though
- The PDF4LHC prescription has been updated to reflect newer generations of PDFs, and new prescription for α_s
- Global PDF sets all planning new releases in near future which will include both HERA2 data and LHC data
  - expect better gg luminosity agreement
- META PDFs are a technique of summarizing the PDF(+α_s) uncertainties for a range of physics processes in a range of center-of-mass energies with just a few eigenvectors
  - they will be used in future updates of PDF4LHC recommendations
  - we used 7-14 TeV in current set of META PDFs, but are now looking at 33 and 100 TeV
  - start with Higgs-related processes; maybe some standard BSM cross sections as well

Coming in the near future

The Black Book of Quantum Chromodynamics

A QCD primer for the LHC era

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